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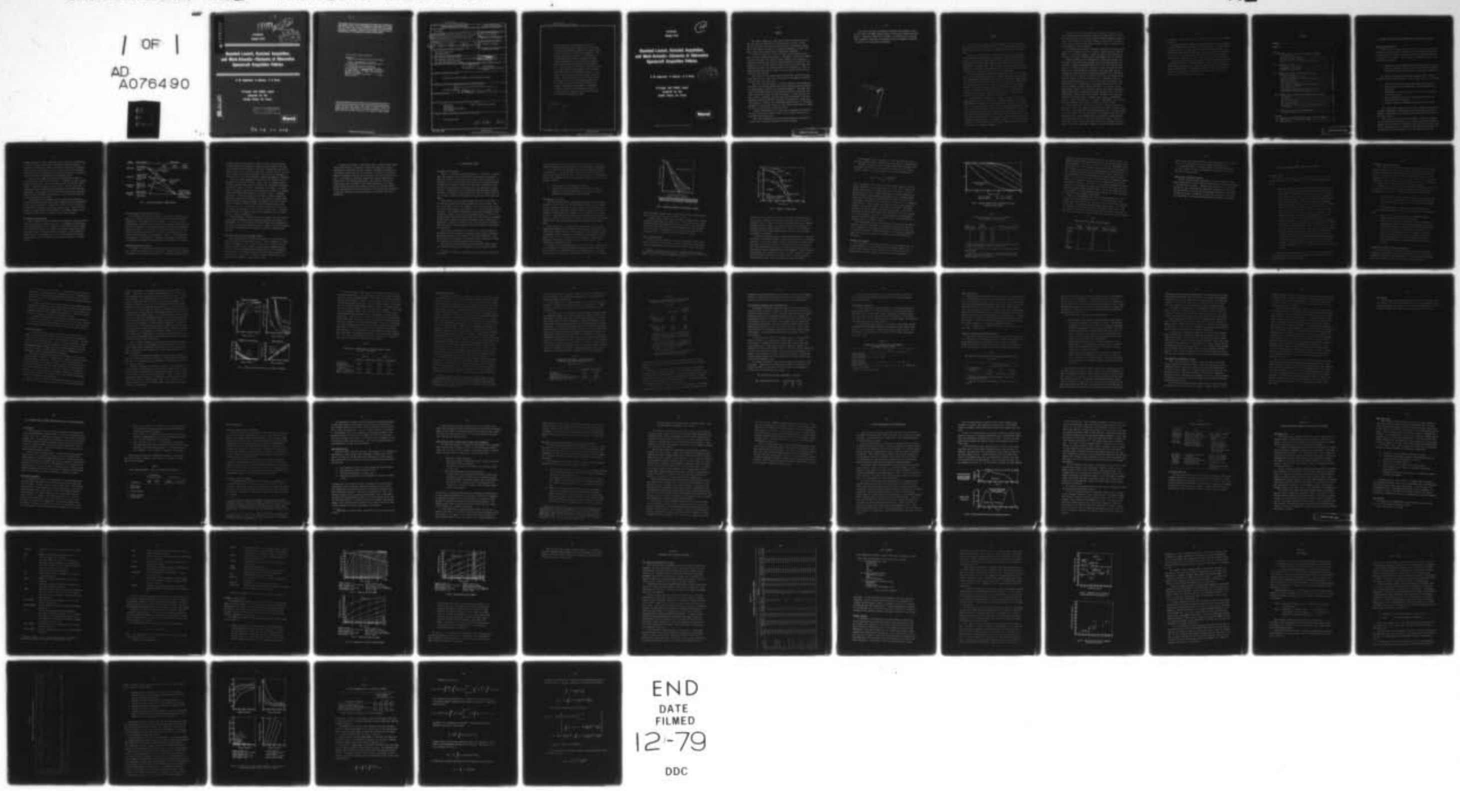

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Bunched Launch, Bunched Acquisition, and Work-Arounds—Elements of Alternative Spacecraft Acquisition Policies

B. W. Augenstein, D. Dreyfuss, A. G. Parish

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA. 90406

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A review of spacecraft acquisition policy to determine whether, and to what degree, variations in acquisition methods can lower total space system costs without loss of operational capability. The authors conclude that there is an alternative to the conventional acquisition strategy; it would involve changes both in the conventional procurement process and in the conventional launch process. This alternative decreases system costs while increasing operational capability, and is equally useful with either an expendable booster or a Space Transportation System recoverable booster used for launch. The concept would call for bunched launch (launching the total mission-required spacecraft in as short a time as possible) and bunched procurement (buying the total number of satellites needed at one time) necessatating accomodations to institutional contraints and the present legal and regulatory framework. (JDH)

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PREFACE

This report summarizes a Rand study project initiated in 1975 by Maj. Gen. Henry B. Stelling, Jr.--then Director of Space, Hq USAF. The study reviews spacecraft acquisition policy to determine whether, and to what degree, variations in acquisition methods can lower total space system costs without loss of operational capability.

A review of spacecraft status in several major programs showed many spacecraft remaining unlaunched. The numbers of satellites needed for various missions had originally been computed using standard reliability estimation procedures to define operating lifetimes for the satellites. But in many cases the satellites in orbit had longer than estimated lifetimes, and unused spacecraft were stacking up. Some of these pipeline spacecraft may never be used or may be used only after extensive modifications.

The authors of this report examined spacecraft acquisition strategies with an eye to more efficient acquisition strategies, resulting in lower total life cycle costs.

They first reviewed inputs to current procedures for determining the number of satellites needed and the associated satellite production and replenishment schedules (for specified missions). They then identified the estimated satellite reliability function as the input that tends to drive the output of these procedures. If these were not the most realistic estimates, what new ones could be provided? They next attempted to match alternative acquisition strategies to revised lifetime estimates. Finally, they determined quantitatively, to the degree possible, the system cost effects of such revised acquisition strategies and where it was possible to minimize costs.

A prime consideration at all times was to maximize the fraction of the time in which the system carries out its specified mission at an acceptable performance level.

This report synthesizes the generalized substudies undertaken to address these issues and summarizes the major findings.

This report and the contributing substudies were prepared as part of the Project AIR FORCE research project "Spacecraft Acquisition Strategies." The report should be of interest to a broad sector of the Air Force planning, operations, and system acquisition community concerned with space as an operational environment.

SUMMARY

In 1975, USAF requested The Rand Corporation to evaluate options for spacecraft buys considering system costs, operational capabilities, and possibilities for spacecraft program/acquisition strategy tailoring.

Although we were initially interested in all satellite programs, we gradually concentrated on the programs that involved a large total buy of spacecraft and sought a long mission duration and in which the technology, the enemy threat, and our consequent mission needs were evolving at a moderate rate. These programs include surveillance, communication, navigation, environmental observation, and others that typically require several spacecraft in orbit simultaneously.

For these satellite programs we conclude that there is an alternative to the conventional acquisition strategy involving changes in both the conventional procurement process and the conventional launch process. This alternative concurrently tends to drive system costs down and operational capability up. It is equally useful whether an expendable booster or the Space Transportation System (STS) recoverable booster is used for launch (STS has prospective benefits of reductions in launch cost, increases in launch reliability, and possibilities for on-orbit test, checkout, recovery, and repair).

This conclusion is suggested by review of satellite reliability undertaken as a part of the project. Satellite reliability is a major determinant of the number of spacecraft needed to support a given mission for a stated program lifetime. Our review indicated that classical ways of assessing satellite reliability are generally conservative and that this conservatism increases procurement requirements. In turn, the observed lifetimes depend on the intensity and thoroughness of testing, and on "work-arounds," or the ability of the ground crew, through command and control links, to circumvent, moderate, or delay the effects of otherwise serious failure events in orbit (apart from such activities as switching to redundant components).

Together with the observation that the dormant lifetime of satellite components and subsystems is generally a large multiple of the activated lifetime, these findings suggest a bunched launch utilization concept (launching the total mission-required spacecraft in as short a time span as possible) and dormant storage in orbit of satellites not needed initially for the mission.

The bunched launch concept eliminates the need for reliance on any but the most fundamental output of computer simulations--the expected numbers of spacecraft needed to support an explicitly defined mission. Questions of specific scheduling and replenishment times are avoided.

Bunched launches can be associated with bunched procurement, although these two actions are separable and can provide benefits independently. Bunched procurement implies that once a decision has been made on the probable numbers of satellites needed, one buys the total number to the same design specifications at the same time, thus increasing the production rate, compressing production time, exploiting learning effects, producing "identical" satellites, and minimizing the production costs of the total spacecraft buy. Exhaustive tests, including orbital operation, on one satellite ("proto-flighting") will then validate all the satellites. One could then launch these satellites on demand (to replace failed satellites). For higher system availability, however, the satellites could be launched on anticipated demand (launching a replacement before anticipated failure, with the replacement a dormant spare until needed). We know of no high confidence way to determine when a satellite will require a replacement, however. Another possibility is to launch a replacement, or an initial satellite together with a spare, to stock up spares in orbit.

Bunched launches are one way to realize the kinds of benefits one would get if there were indeed a foolproof way of predicting when failures occur. The satellites rot needed immediately after a bunched launch are stored dormant in orbit and turned on as necessary when the earlier satellites fail. This strategy has the possibility of maximizing the operational availability of the total spacecraft system. It may be particularly useful if the satellites are stored in shuttle-accessible orbits for recovery and repair. However, given the reliability levels

we consider, storing in any orbit, including synchronous orbit, appears attractive.

This bunched launch, bunched procurement strategy is one possibility for an alternative spacecraft acquisition policy. It would provide a min/max approach to spacecraft cost/operational availability. The system cost reductions could be used to support several new system initiatives in the programs we consider: newer, more complex programs; more programs; added missions; and added survivability enhancement.

There are institutional impediments to the bunched launch, bunched procurement strategy: It would imply new methods for doing business with the DoD and entail additional persuasion of the DoD and Congress. When deciding whether to experiment with this strategy, the Air Force will have to balance the convenience of business as usual with the possibility of new initiatives in space.

CONTENTS

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I. INTRODUCTION--THE ISSUES AND FINDINGS DISCUSSED QUALITATIVELY

THE SCOPE OF THIS STUDY

In March 1975, The Rand Corporation, at the request of AF/RDS and the Office of the Secretary of the Air Force, initiated an examination of the Air Force's current spacecraft procurement strategies and those it could use in the 1980s. This study was to emphasize classical system acquisition issues:

- Develop and evaluate alternative spacecraft acquisition strategies that minimize life-cycle costs of sytems while maintaining appropriate and desirable system operational capabilities.

The spacecraft acquisition strategies examined need to reflect certain objectives and constraints to be optimally useful. They should:

- Not unduly overload or exhaust the acquisition pipeline.
- Consider issues of new development versus technological obsolescence.
- Accommodate to new capabilities, such as the Space Transportation System (STS).
- Have identifiable relations to institutional issues that bound acquisition strategies.
- Exhibit a realistic economic and program planning utility.

This study clearly cannot cover the entire spectrum of spacecraft research, development, procurement, launch, and operational issues. However, we concentrate on acquisition and acquisition-related issues for three reasons.

First, some current satellite procurement strategies apparently are not particularly cost-effective. Military satellite programs may acquire excessive numbers of satellites (and thus find themselves paying for unused spacecraft or retaining and operating an outmoded system because they are constrained to use the satellites that were

already purchased). Excess procurement can, of course, occur with any concept of spacecraft acquisition, including bunched procurement. Alternatively, programs may acquire insufficient spacecraft to maintain the desired system capabilities over the projected system mission duration (possibly resulting in serious outages, reductions in capabilities, or expensive reestablishment of production lines).

Second, in the coming decade spacecraft monies may be more restricted than they have been in the past. To maintain at least current levels of capabilities, the Air Force must reduce system costs, particularly if additional capabilities are desired. One way to do this is to make procurement strategies more consistent with updated satellite experiences. For example, if satellites have a longer life expectancy than is usually estimated, fewer satellites need be procured and significant savings can be realized.

A third reason for reviewing satellite acquisition strategies is that new mission requirements are being formulated and new technologies are being made available to enhance the utility of space systems for supporting both strategic and general purpose forces. There is little reason to assume that past unsatisfactory procurement strategies will be adequate to meet future demands for space system support.

THE ROLES OF SPACE SYSTEMS

Space capabilities are important now for support of operating forces and will become more important with time. The examples of four generic space systems listed in Fig. 1 now have, or will have, primary capabilities that provide major force support for General Purpose Forces and Strategic Forces. In addition, these capabilities can be combined to provide still further enhancement of the striking power of the operational forces, as the few examples (from a much larger list) indicate in Fig. 1.

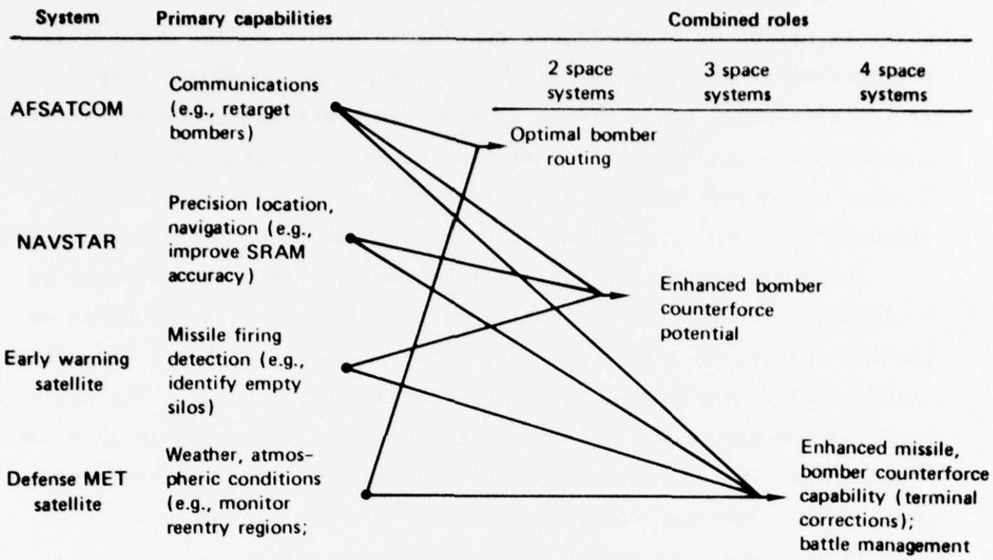

Fig. 1 — Roles of space systems — 1980s examples

The Efficiency Context of Space Systems

If one holds the nature and quality of the primary capability constant, it is possible to define a useful concept of efficiency in the production of force support by space systems. In this case, system survivability, availability, and continuity of operation become the measures of performance that are comparable over different space programs. With these measures it is possible to allocate resources to space programs that support military forces so that no one program can be improved without degrading the performance of another. This allocation of resources is not efficient if improving one program's availability or survivability degrades the availability or survivability of another.

Bunched Procurement or Launch

In bunched procurement all spacecraft needed to satisfy a mission for a given mission duration are acquired in a compressed time schedule, to optimize the spacecraft production rate. In bunched launch, after a

suitable period of proto-flight testing to ensure design integrity, the spacecraft are launched in a compressed time schedule, with some of the spacecraft being stored in orbit in a dormant state and the remainder being used to satisfy mission needs. Bunching affects the conduct of spacecraft R&D and operations--such issues as technological obsolescence, use of skilled manpower, and R&D programmatic constraints.

There are strong arguments for believing that spacecraft can be designed for very long lifetimes. In this case, a strategy based on placing spacecraft into orbit very early in the mission has attractive operational features as well as substantial cost savings. The spacecraft not needed in early parts of the mission are stored in a dormant state and activated when necessary to replace a failed or degraded spacecraft. Systems are stored in orbit and can reduce outage time when an activated spacecraft fails, the space system is automatically proliferated and enhances survivability potential, there is no temptation to "improve" systems in orbit, which sometimes leads to new failures, and so on. The concept of bunched launches does depend on low failure rate dormancy for the systems stored in orbit. We assume that provisions for dormancy require costs comparable to the storage costs of systems in warehouses.

Bunched launches lessen reliance on the complex (and often unrealistic) models providing computer-generated schedules for launch, replenishment, etc. We need only the simplest (and, with reasonable input data, the highest confidence) output of computer model calculations--the total expected numbers of satellites needed for a given mission duration

POSSIBLE EFFECTS ON THE PROCUREMENT PROCESS

With long spacecraft lifetimes and bunching, we have powerful arguments for Multi-Year Assurances (see Sec. IV) for funding of at least some space programs. First, there are direct cost savings as well as probable implicit resource allocation improvements stemming from the way space mission development and production phases can be conducted. Second, there is a minimum cost way of ensuring high availability in space missions. Third, it is possible to inject rigorous price competition in procurement of major space systems.

In bunched procurement a proto-flight phase (conducted under RDT&E funds) would validate a design that would then become the standard spacecraft for satisfying the space mission. Normally the winner of a proto-flight competition would be authorized to produce the necessary number of spacecraft required for the mission, but this need not be the case. A new round of contractor competition could be conducted for *production* of the validated spacecraft. That contract could go to someone other than the winner of the RDT&E competition, or a shared (multi-contractor) production contract could be let, with the shares perhaps determined by cost and performance of the individual contractors. In that way competition could in principle be maintained even *during* production.

II. RELIABILITY ISSUES

THE NATURE OF THE ISSUES

Space is a generally benign environment for satellites. Most DoD, NASA, and commercial satellites function much longer than expected. Many have survived in space many times longer than was predicted. Inadequacies in the present predictive capability for orbital lifetimes are apparent. Estimates derived from piece-part[1] reliability calculations using failure rates constant in time are generally very conservative. Replacement of the calculations with empirically derived reliability estimates--by observing actual in-orbit failures--will result in fewer satellites being needed to support successful space programs.

Unfortunately, not all space programs have been so successful. A few have been plagued with design problems and early failures. The poor performance of these few programs is not predicted by either the piece-part calculations or the simplest form of the empirically derived estimates. This bimodal distribution of satellite performance is not considered, usually, in satellite procurement practices. Still, it is an empirically demonstrated finding that sound design (which eliminates evident failure paths) and intensive testing results in long-lived spacecraft; in addition, certain activities (work-arounds) can defer or alleviate failure situations once the spacecraft begins to experience these in orbit.

Research has demonstrated the inadequacy of current methods of estimating satellite reliability functions (specifically, estimation methodologies based on the constant failure rate assumption). This was the finding of a number of independent studies conducted in industry, NASA, and in other government research centers.

Reliability functions and mean mission durations (MMDs) derived from conventional piece-part calculations based on constant failure

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[1] Resistors, transistors, capacitors, etc., which are basic building blocks.

rates understate satellite reliability, and, when used as inputs to computer simulations, they overstate mission procurement requirements.

It is useful to see what might contribute to higher than expected reliability. At least two factors may be particularly important, once we have assumed that the basic spacecraft design is sound and that piece-parts, components, etc. have been intelligently selected and rigorously screened:

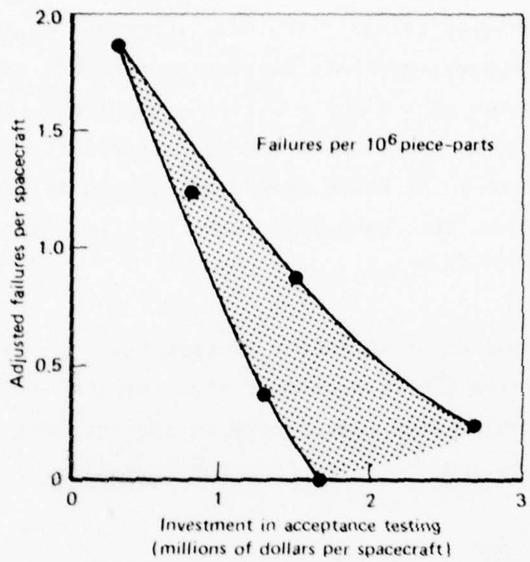
1. The thoroughness or intensity of testing.
2. The activities ("work-arounds") of satellite designers, managers, and system controllers in correcting spacecraft malfunctions and anomalies from the ground.

<u>Thoroughness of Testing</u>

One can postulate several pre-flight activities to eliminate bad satellites. One of these is extended ground testing of major systems or fully integrated satellites. Some contractors producing more successful satellites than other contractors have in fact adopted such intensive testing strategies. Examples of the consequences are shown in Fig. 2. The shaded region illustrates the general trends seen; because the spacecraft have different numbers of piece-parts, all observed failure rates have been normalized to those pertinent to 10^6 piece-parts.

There appears to be a significant correlation, in that the thoroughness and intensity of acceptance testing results in satellites that suffer fewer orbital failures. Such testing is fairly inexpensive and is generally a small fraction of the total cost attributable to reliability (see App. B). Whether such testing exceeds specification requirements or reflects a stringent view of testing strategies is a subject worth additional review.

Because of such experimental data, we are reasonably confident that it is possible to routinely manufacture complex spacecraft whose ultimate failure mode is dominated by wearout phenomena (e.g., lifetimes of the order of ten years); lifetimes of 65 to 90 months (5 to 8 years)



Note: Each circle represents a different large-scale spacecraft program. The programs and their contractors are deliberately not identified. The figure is based on Aerospace Corporation data gathered under NASA contract.

Fig. 2 — Spacecraft reliability versus investment in testing

based on random failures appear conservative and quite easily achievable with careful design and intensive testing.

Another example of the value of testing is shown in Fig. 3, which is based on data found in an RADC study.[2] In this case a nice correlation was again found between the piece-part failure rate (for both energized and dormant states) and the rigorousness of the testing. The testing rigor is exemplified by the period of burn-in (the subjection of parts to stressful operation must be survived).

Role of "Work-Arounds"

In the satellite community, the term "work-around" refers to the ingenious activities of designers, managers, and system controllers in correcting malfunctions and anomalies that occur in orbit that would

[2] Rome Air Development Center Report, "Dormancy and Power On-Off Cycling Effects on Electronic Equipment and Part Reliability," AD-768 619, August 1973, prepared by Martin Marietta Aerospace.

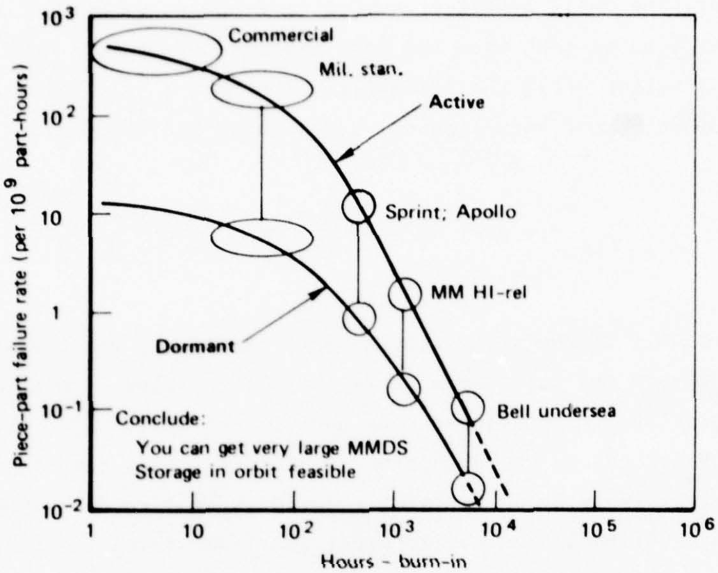


Fig. 3 — Reliability – Empirical data

otherwise result in satellite failure. The dedication and expertise of personnel at SAMSO, the Aerospace Corporation, and the Air Force Satellite Control Facility and Test Center and the aerospace community frequently enable satellites to function beyond their expected life through such work-arounds. However, this effect is not included in the usual satellite replenishment models, which are used to support procurement requirements.

Current replenishment models generate representations of satellite lifetime by using random numbers in conjunction with various reliability functions. For instance, Rand's Satellite Availability Simulation Program (App. A) uses two reliability functions for satellite lifetime--one as determined by the piece-part reliability function and one as determined by wearout phenomena--using the minimum of the two simulated lifetime numbers to represent satellite lifetime. Aerospace Corporation's Generalized Availability Program (GAP) is similar but adds a likelihood that early failures dominate the other two numbers.

Work-arounds permit a satellite to "fail" more than once and to continue operating until a failure occurs that cannot be worked around.

Appendix C shows that when the work-arounds do not influence the reliability function R(t), the reliability function $R_k(t)$, (with an arbitrary number, k, of work-arounds) is given by the expression

$$R_k(t) = R(t) \sum_{n=o}^{k} \frac{[-\ln R(t)]^n}{n!} .$$

This is reasonable if the satellite contains many parts and the work-arounds compensate for only those parts that have failed. In the following calculations it is assumed that this is the case. With this assumption, $R_k(t)$ can be easily approximated in existing computer simulation models, simply by multiplying together $N_w + 1$ random numbers with uniform distribution on the interval [0,1] and using the result to determine a satellite lifetime through the inverse of the reliability function, R(t). Figure 4 shows the results of using this technique to calculate the effective life of satellites used in one of the SAMSO programs, for various numbers of assumed work-arounds. The effect of incorporating work-arounds dramatically changes the effective reliability of the satellite. For this real-world example, one work-around increases satellite mean-life by a factor of 1.7; two work-arounds increase it by 2.3, as shown in Table 1.

When work-around effects are considered, the effective mean-mission duration depends on the number of work-arounds expected per satellite. Also, comparisons of achieved versus predicted satellite life that fail to consider the effect of work-arounds may lead to spurious conclusions about the efficacy of reliability functions for predicting satellite lifetimes.

DORMANCY AND BUNCHING

The feasibility of designing satellites with assured long life permits consideration of several interesting procurement options. The bunched launch concept involves satellites that would be stored in a dormant state on orbit, permitting very high system availability.

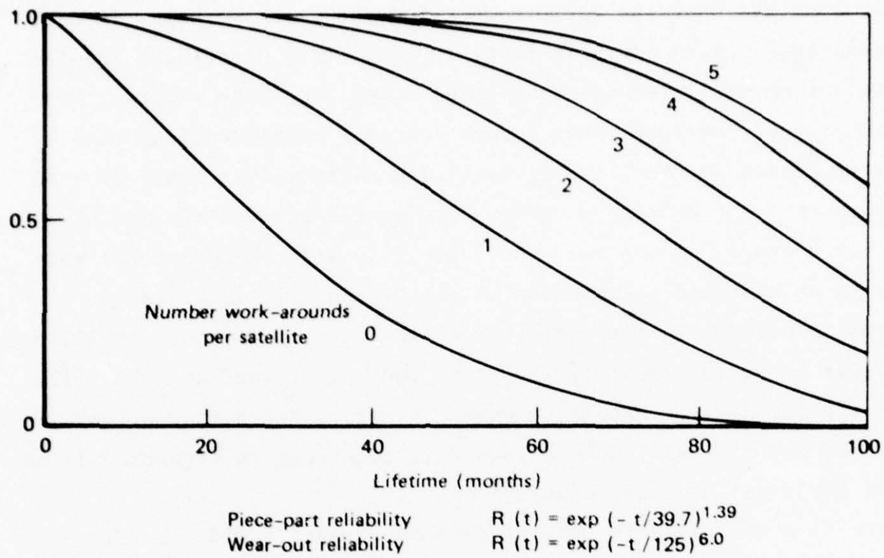


Fig. 4 — Effective satellite lifetime distributions for various numbers of work-arounds

Table 1

EFFECTIVE MEAN SATELLITE LIFE AS A FUNCTION OF THE NUMBER OF WORK-AROUNDS[a]

Number of Work-arounds	Mean Satellite Life (mo.)	Ratio[b]	Satellites Needed for a 4-Satellite System[c]
0	34.6	1/1	14
1	59.5	1.7/1	8
2	80.9	2.3/1	6
3	100.3	2.9/1	5
4	118.3	3.4/1	4
5	135.3	3.9/1	4

[a]This table provides the mean of the work-around distribution of the reliability function shown in Fig. 1.

[b]This is the ratio of mean satellite life with and without work-arounds.

[c]For ten years of operation, assuming perfect satellite launch/initialization probability and all satellites having the same number of work-arounds.

Although on-orbit data on dormant satellites are limited, current information suggests that the failure rate for the inactive boxes in dormant satellites is very low. In fact, in a specific experiment involving reactivation of 34 redundant boxes on seven satellite programs, no box failures were observed, even though dormancy considerations were not a prime factor in the original satellite designs (see Table 2). In this experiment, the average dormancy time ranged between six and 41 months. In a sense, of course, every satellite with redundant elements that are to be switched on when one of the elements fails yields an experiment in dormancy. Therefore, if we assume that dormant satellites do not begin to degrade appreciably until they are turned on (the failure rate for the dormant satellite boxes is zero), the number of satellites needed for a single bunched launch is identical to that calculated by any of the usual computer simulations.

There is a considerable body of data on dormant failures. Some of these data are summarized in Fig. 3. The data shown there give dormant piece-part failure rates directly, and we also show the estimates of the ratio: energized/dormant piece-part failure rates. The better the reliability of the energized part, the smaller that ratio is. But for the class of parts used in good spacecraft, this ratio should be of the order of ten or more, suggesting that for spacecraft with an energized

Table 2

TURN-ON OF UNITS AFTER IN-ORBIT DORMANCY

Program	Number of Units	Average Dormancy Time (days)	Number of Failed Units at Turn-on
PIONEER	3	227	0
VELA	5	333	0
DSP	3	340	0
DSP	8	543	0
DSCS II	3	180	0
NATO	8	1246	0
TACSAT	4	510	0

life of, say, five years, failures in the dormant state in a period of five to ten years should have an extremely low probability.

These data allow us to assume, whenever we discuss bunching or the use of spares in orbit, that dormant failures in a five to ten year period are negligible.

Implications of High Reliability

Because long energized and dormant lifetimes of spacecraft have been demonstrated, the next concern is how best to use these conclusions in an acquisition strategy. Although long lifetimes reduce the total system buy, they also permit the concept of bunching to be effective. We next consider in more detail the bunching possibilities that permit substantial savings in addition to those made possible by exploiting the higher MMDs in conventional launching and procurement strategies.

III. BUNCHED PROCUREMENT, BUNCHED LAUNCH ISSUES

THE BASIC CONCEPT

The bunched procurement, bunched launch concept refers to a satellite procurement and utilization policy with the following characteristics:

1. Satellite design life and reliability function characteristics are matched to an entire technological generation in the mission payloads. Thoroughness of acceptance testing is assumed to be high enough to ensure very low frequency of random piece-part failures in orbit. This implies that satellite lifetimes are determined primarily by wearout or depletion phenomena.
2. Satellite production geared to a proto-flight concept, in which one or two satellite prototypes produced and tested on the ground are launched into earth orbit for an extensive further testing period (of some months duration, for example). The validated satellite's subsequent production rate is then optimized for minimum cost after the proto-flight test.
3. Production satellites are launched in one bunch (or two bunches) as quickly as possible, and stored in a convenient orbit. This orbit could be the operational orbit. It could also be a checking orbit, which is accessible by the STS. The satellites would be stored in the checking orbit for a certain period, after which some spacecraft that have suffered failures may be retrieved for repair, or some of the checked-out spacecraft may be placed in actual mission orbit, with some active and others dormant. These orbits may be combined in several ways. No scheduling constraints, or very minimal ones, occur after bunched launch.

Conducting a satellite program in this way may well result in salutary institutional and organizational effects on both the RDT&E and operations phases of space capabilities.

TECHNICAL FEASIBILITY ISSUES

Many analysts still consider alien the notions that random failures can be eliminated in a satellite by sufficiently exhaustive acceptance testing and that the lifetime of a satellite, with "work-arounds" possible, is determined largely by wearout phenomena and depletion of expendable resources. This is *especially* true of those with a statistical orientation. The evidence, if not yet wholly conclusive, is persuasive to a growing number in the spacecraft acquisition community.

Furthermore, the concept of "proto-flighting" satellites in the STS era in low earth orbit for a period of testing before injection into synchronous orbit involves a number of operational considerations:

1. Low earth orbit testing involves deployment of antennae, solar arrays, etc. that would have to be restored and secured prior to injection into mission orbit by the Inertial Upper Stage, (IUS).
2. The IUS design life in orbit may be unduly constrained.

In the long run, neither of these conditions needs to be constraining.

3. To date, there has been significant uncertainty about or opposition to the storage in orbit concept.
4. There is at present no cost effective plan for developing a capability to recover satellites from synchronous orbit for repair and refurbishing. This factor drives the requirement for low orbit testing if STS recovery is to be used. Of course, at the reliability levels we consider, injection directly into the mission orbit is certainly an option for both a proto-flight test and the operational spacecraft. Hence we do not consider the uncertainty factors to be constraining.

PRACTICAL QUESTIONS ON THE BUNCHING CONCEPT

To what extent would this policy enhance or detract from system reliability, availability, or outage characteristics? Can such policies eliminate dependence on detailed computer modeled scheduling techniques such as those given by SASP or the Aerospace Corporation GAP?

To what extent is this policy less costly than current practice because of: (a) minimization of inflation effects, (b) satellite production rate optimization and learning curve effects, and (c) finite lifetime SPOs with associated reduction in management overhead and personnel costs?

To what extent would this policy eliminate "rear guard" technology development (developments that produce marginal changes or improvements), and free contractor and program office resources for work on major improvements rather than incremental improvements? To what extent would design life decisions constrain system modernization?

To what extent would this policy enhance or detract from system survivability, by virtue of its inherent proliferation of space systems?

We shall discuss these questions in turn. Some of this discussion is necessarily qualitative but in many cases we can be quite precise.

SYSTEM PERFORMANCE

For purposes of this report, a system outage occurs whenever the number of operational satellites in space falls below the minimum required for successful performance of the mission or function. The major factors influencing outage are: (1) the satellite reliability characteristics as described by the satellite reliability function; (2) the replenishment launch schedule; and (3) the launch response time (LR)--the time to replace a satellite that has failed, assuming that a replenishment satellite and launcher are available.

The bunched procurement and launch policy compresses the procurement and launch schedule to the maximum degree and uses on-orbit storage for replenishment satellites. This affects system availability and maximum outage in several ways. First, it reduces the outage time during which replenishment satellites and launchers are not available because of procurement scheduling. Second, it reduces the outage time caused by the finite response time of launch facilities and resources at the national launch centers, which occurs even though replenishment satellites and launchers are available.

Third, it increases satellite utilization during the program period, in effect shifting satellite capacity from the post-program period

(where it contributes to technological obsolescence) to where it is needed. These effects are clearly demonstrated in Fig. 5, which plots four important system performance measures against the number of satellites procured. The system designer selects from these parameters to evolve a program that will meet the needs of the user community and budgeting authorities--e.g., for LR = 2 months and 90 percent system availability using a conventional launch strategy, 17 satellites are needed. For any given number of satellites the bunched launch approach is significantly better than the conventional approach with respect to availability and maximum outage. It is slightly better with respect to the excess program life performance measure. The only performance measure in which the bunched approach is worse than the conventional approach was the probability of early program termination. Because it uses satellites more intensively during the program period, the bunch procured system will always have a slightly higher probability of early termination for a fixed number of satellites. However, the effect of this termination is dramatically less than for the conventionally procured system; furthermore, during the program period the bunch procured system has higher overall availability.

All the sample calculations reflected in Fig. 5 are made through the detailed computer model simulation described in App. A. The detailed computer model simulation is useful in *comparing* various strategies, even though we may be skeptical of the absolute values of the numbers produced.

The enhanced performance available in bunched launch systems permits space missions with fewer satellites. An example will illustrate how this is so depending on the combination of requirements specified for the space system.

Consider the number of satellites required for two alternative sets of requirements specifications. The first set, denoted SPEC 1, calls for 95 percent availability, two months maximum outage duration, and 0.1 probability of early program termination. Figure 5 shows that the conventional approach requires a 17-satellite system and a one month (or slightly shorter) launch response time. Fewer satellites, or a launch response time greater than one month, would make it impossible to meet the requirements.

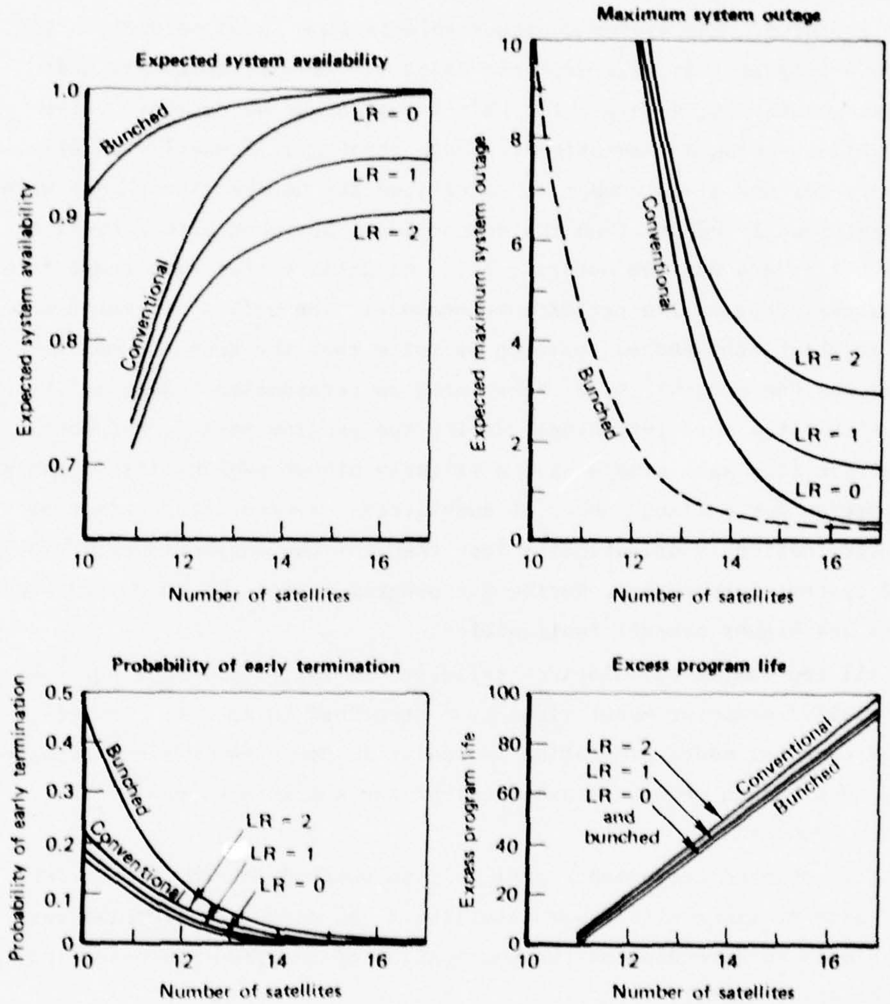


Fig. 5—System performance as a function of number of satellites

The bunch procured system using a 13-satellite system can easily meet these requirements. The performance of the two systems is shown in Table 3 under the heading SPEC 1. The excess system life associated with the conventionally procured system is nearly as large as the original mission program life itself. Also the bunched launch system would cost less than the conventionally launched system by an amount equal to the cost of four satellites plus their associated launchers. The second set of requirements, SPEC 2, calls for 90 percent availability, six months maximum outage duration, and 0.1 probability of early program termination. Again from Fig. 5 one can see that both the conventional approach (with one month launch response time) and the bunched approach require 13 satellites to meet the requirements. For SPEC 2 the bunched procurement approach would still provide cost savings, even though the same number of satellites is procured. The program and performance characteristics for conventionally and bunch launched systems to meet SPEC 1 and SPEC 2 are summarized in Table 3. Here the bunched approach costs less than a conventionally procured system, but the savings depend upon the availability and outage specifications.

Table 3

COMPARISON OF CONVENTIONAL AND BUNCH PROCURED SYSTEMS
FOR SPEC 1 AND SPEC 2

	SPEC 1		SPEC 2	
	Bunched	Conventional	Bunched	Conventional
Availability	99.0	94.9	99.0	90.5
Maximum outage	1.0	1.5	1.0	5.9
Probability of early termination	0.06	0.01	0.06	0.03
Number of satellites	13	17	13	13
Excess program life	31 mo.	98 mo.	31 mo.	34 mo.

THE TWO-BUNCH VARIANT

Launching all satellites as quickly as possible in a single bunch procured system can, in certain conditions, penalize the bunched launch strategy relative to the cost of the conventional procurement approach. The conventional procurement approach permits observation of the satellites' orbital performance, and satellite/launcher assets are then expended only as needed. The bunched approach discussed previously expends launcher and spacecraft assets, which might, in hindsight, not be needed. Consider, for example, the alternative conventionally launched and bunched launch systems capable of meeting the two sets of requirements just discussed. SPEC 1 required 13 satellites for the bunch and 17 for the conventionally launched systems, and SPEC 2 required 13 satellites in both approaches. However, after simulating these two programs, one could see that on the average (at "Probability of Early Termination" equal to 0.5, which would not be a very conservative planning basis for many programs), for SPEC 1 and SPEC 2, only eight launches would have been made for the conventional and ten for the bunched launch systems at program conclusion. Thus, for SPEC 2, the bunched launch system would have expended three satellites and launchers needlessly in a sense, and the conventionally launched system would have been able to avoid the cost of three launchers and the associated satellites. Likewise, for SPEC 1 the bunched launch system would have expended three satellites and launchers needlessly, whereas the conventional approach could have avoided launcher costs for nine unneeded launchers.[1]

To eliminate this characteristic of the bunched launch/procurement concept, we can use a variant of the bunched launch concept involving two bunches. Satellites will be procured and launched in two bunches, with the procurement and use of satellites in the second bunch contingent on the observed performance of satellites in the first bunch. For example, for both SPEC 1 and SPEC 2, ten satellites would be procured

[1] In this example we are not concerned with maintaining a high SA or keeping the expected maximum system outage at low levels. Figure 5 shows the dramatic drops in SA for the conventionally launched case when we reduce the number of satellites. We cannot *simultaneously* have a high SA *and* exploit the observed behavior of satellites with the hope of minimizing the number needed.

in the first bunch and up to three satellites would be considered for the second bunch. The satellites and launchers in the second bunch would be available in month 70.

The degradation in system performance due to the change in availability of satellites in the second bunch is negligible, as is shown in Table 4 for the 13-satellite case, with three satellites in the second bunch.

The expected costs of conventional and two-bunch procured systems are compared in Table 5 for systems designed to SPEC 1 and SPEC 2 requirements. For this table it is assumed that regardless of the number of satellites procured, the number of satellites launched in the first bunch is that associated with a 50 percent probability of early termination. For the bunch procured system, even though 13 satellites were necessary to provide the desired confidence in meeting SPEC 1 and SPEC 2, only ten satellites are launched, on the average; launch expenditures for only these ten satellites are included. For the conventionally procured system, only eight satellites are launched on the average, as extrapolations of Fig. 5 will show; however, 17 satellites are procured for SPEC 1 and 13 for SPEC 2. For SPEC 1, should it turn out that the additional satellites were needed, there would be further costs of $25 million per launch. Maximum additional costs for nine launches at $225 million would be required for the conventionally

Table 4

PERFORMANCE COMPARISON OF TWO-BUNCH VARIANT
WITH THE BASIC BUNCH PROCURED SYSTEM

(13 satellites)

	One Bunch	Two Bunches
Availability	99.17	99.21
Maximum outage (mo.)	0.95	0.87
Probability of early termination	0.056	0.050
Excess program life (mo.)	31	32

Table 5

EXPECTED COSTS OF CONVENTIONAL AND TWO-BUNCH PROCURED SYSTEMS FOR SPEC 1 AND SPEC 2

($ millions)

	Conventional	Two-Bunch *Variant*
SPEC 1		
Satellite costs	595[a]	377[b]
Launcher costs	200[c]	250[c]
Total cost	795	627
SPEC 2		
Satellite costs	455[d]	377[b]
Launcher costs	200[c]	250[c]
Total cost	655	627

[a]Nominal satellite cost x number of satellites × learning factor = ($35 million/satellite) × (17 satellites) × 1.0; 100 percent learning assumed.

[b]($35 million/satellite) × (13 satellites) × 0.83; 95 percent learning assumed (i.e., costs drop by 5 percent for each doubling of the number of spacecraft procured).

[c]$25 million per launch.

[d]($35 million/satellite) × (13 satellites) × (1.0); 100 percent learning assumed.

procured system under SPEC 1, whereas the two-bunch procured system would involve only $75 million in potential additional costs for three launches.

Obviously the two-bunch variant reduces the number of satellites in orbit, thus decreasing the benefits of survivability through proliferation of the bunched approach. Satellites in storage on the ground forgo some of the possible enhanced survivability benefits to storage in orbit. The likelihood that these satellites in ground storage would be technologically upgraded is also increased.

The above analysis indicates that the cost advantage of the bunched procurement approach is, like the system performance advantage, highly

dependent on system requirement specifications. In the cases examined, however, the bunched procured system still costs less than the conventionally procured system, and provides better system performance.

COST EFFECTS--LEARNING CURVES AND PRODUCTION

In bunched procurement, spacecraft can be procured over shorter periods of time, possibly resulting in reduced unit costs from the more efficient production rates. More efficient production rates can result from the creation of an optimized production line, more emphasis on standardized spacecraft, substitution of capital for labor, better use of production and test facilities, and optimum mixing of concurrency and sequential production. This has seldom been demonstrated in the unmanned spacecraft area, because most space projects stretch procurement schedules to hedge against uncertainty and reduce annual funding requirements. The resulting low production rates permit little, if any, learning.

To illustrate the effects of learning, suppose as a conservative example we take a case resulting in a small number of satellites in the total buy. Consider a ten-year program that requires four satellites continuously in orbit with a satellite MMD of 65 months, the probability of successful launch equal to 95 percent, and the probability of need level equal to 10 percent. In this case, nine satellites are needed. At an assumed cost of $35 million per satellite, without considering modularization, the total spacecraft buy would cost $315 million (the "No-Learning" case).

In bunched procurement, nine satellites would be procured in about five years. Allowing for an additional investment of $15 million in tooling to produce spacecraft at the higher rate, the following *net savings* over the No-Learning case accrue:

NET SAVINGS WITH BUNCHED PROCUREMENT, $ MILLION

No. of Spacecraft Procured	Learning Curve Slope		
	95%	90%	85%
9	43	78	122

With a learning slope curve in the range of 90-95 percent, the *savings* of $78 to $43 million could be 25 to 14 percent of the base cost of $315 million.

COST EFFECTS--INFLATION

To investigate the possible advantages of bunched procurement accruing from reduction of inflation penalties associated with procurement policies involving longer times, a spacecraft and guided missile price index was used in "typical" production schedules for this nine-spacecraft case. We can then characterize typical "normal" and "bunched" procurement patterns as shown in Table 6.

The inflation-related savings of the bunched versus normal funding pattern of $27.0 million is about 8.5 percent of the base cost of $315 million. A typical effect of bunched procurement shows up here: The peak single year funding rates are higher than the normal procurement cycle peak values.

Table 6

COMPARISON OF INFLATION EFFECTS FOR BUNCHED AND NORMAL FUNDING PATTERNS

	Year												
Case--Nine Satellites													
Bunched Procurement	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	
Delivery Schedule				4	3	2							
Annual Funding ($M)[a]	14	53	95	91	49	14							
"Normal" Procurement													
Delivery Schedule					4	1			1	1	1	1	
Annual Funding ($M)[a]		14	46	67	42	11	14	28	35	32	21	7	
Inflation Premium ($M)[b]												Total	27.0

[a]Constant 1976 dollars.

[b]Assumes 6.8 percent inflation factor.

COST EFFECTS--SPOs

Additional savings associated with the reduction in System Project Office (SPO) manpower can result from the bunched procurement policy. If the bunched launch concept results in a shorter production program, then those SPO personnel who normally work on that aspect of the program will be needed for a shorter period of time. Other savings result because fewer people will be concerned with the product improvement (post-production) phase of a satellite program, which would not usually occur under the (single) bunched procurement policy. A typical SPO has 100 to 125 people at $60,000 per person (total direct and indirect costs). A 20 to 30 percent personnel reduction achieved from these effects results in a savings of roughly $6 million.

Table 7 summarizes the combined prospective cost savings from these three cost effects.

TECHNOLOGY GROWTH AND OBSOLESCENCE EFFECTS

Under current satellite acquisition practice, production lines are kept continuously open, allowing the latest technological advances to be incorporated into the satellite system, at least in principle, through block changes (the production run is divided into blocks in which each spacecraft undergoes a set of prescribed modifications),

Table 7

NET SAVINGS ASSOCIATED WITH THE BUNCHED PROCUREMENT POLICY[a]

($ million)

No. of Spacecraft Procured	Learning Curve Slope		
	95%	90%	85%
9	64 (20)[b]	100 (32)	144 (46)

[a]Includes additional tooling investment, inflation, and SPO manpower effects.

[b]Percent of "normal" procurement cost shown in parentheses.

and to be retrofitted into satellites that have not yet been launched into orbit. This flexibility is important and vital for satellite systems in which the dynamics of the threat or currency of mission payload technology are of overriding importance and provides hedges against catastrophic design errors that evade detection during test phases and contaminate all satellite systems after they have been irretrievably launched into mission orbit.

This flexibility is not without associated costs.

1. Block changes are frequently incremental and seldom involve revolutionary changes in technology or design. Research and development resources tend to focus on "rear-guard technology" (marginal improvements in the existing satellite). There are somewhat concealed but probably significant actual costs as well as opportunity costs associated with "rear-guard technology" because the attention of the designers is not fully focused on the possible large improvements.
2. Design changes and retrofit of previous satellites in the production series are expensive, generally involve requalification and environmental testing of the satellite, and may create new reliability problems.
3. Conservatism in estimating satellite reliability functions delays putting new technology on orbit and can create pressures to turn good (but technologically inferior) satellites off prematurely or to expand the number of satellite stations in orbit.

The bunched procurement, bunched launch policy eliminates the disadvantages to current practice but at some cost in lower flexibility. Under the bunched procurement, bunched launch concept, satellites would have design lives to match an entire technology generation in the mission payload technology. Incremental improvements and block changes would be eliminated, along with their associated costs and inefficient use of R&D talent and resources. By selecting satellite design life to match a technological generation (the "natural" time during which major

technology advancement and incorporation of that technology into spacecraft design is possible rather than merely incremental technology advancement) in the mission payload, the bunched approach eliminates the tendencies to turn good satellites off prematurely but still ensures the best attainable system availability and outage characteristics.

A penalty is associated with elimination of incremental improvements. Some of the spacecraft may be in dormant storage in orbit for as much as eight or nine years before being actively used. The technology level of these spacecraft is that of the time of mission start.

Block changes and retrofit activity to maintain the state of the art in satellite technology can be costly and limited in usefulness. However, where national priorities dictate, this flexibility can easily be justified. In other cases, the bunched procurement, bunched launch policy should be considered as an effective alternative.

To correct for technological obsolescence in the bunched procurement, bunched launch approach, we would incorporate the *major* technological improvements in an entirely new and upgraded satellite generation at the end of a given discrete mission duration. From a multi-year perspective, the growth of the technology level in the bunched and conventional approaches would be similar, but the technology growth pattern in the bunched case would usually exhibit a more pronounced "sawtooth" pattern. This is true of almost all other military equipment in cases where we want to field and operate stable, thoroughly engineered designs.

SURVIVABILITY/VULNERABILITY EFFECTS

Under current practice, satellite spares are stored in environmentally controlled warehouses subject to possible sabotage action by clandestine agents of hostile countries and terrorist organizations, in addition to the normal risk of damage from natural disaster and industrial accident. Although it would be possible to use geographic dispersal and cover and deception strategems to protect satellite spares in storage or in transit to and from production/test/launch facilities, such precautions are rare.

The bunched procurement, bunched launch policy in effect substitutes storage in orbit for the ground storage of current practice. All

satellites might be stored in an STS-accessible orbit during an initial reliability burn-in period, after which the satellites may or may not be launched into mission orbit storage. In such orbits, satellites are free from the threats described above but are vulnerable to more sophisticated forms of attack.

On-orbit storage increases the number of satellites at risk at any one time to attack by anti-satellite systems (ASAT) and covert degradation. However, it also expands the enemy's target complex and complicates his task, especially with respect to covert degradation attack. Shuttle accessibility of spares would be one counter to covert activities. The enlarged target complex associated with storage on orbit would increase the attacker's problems by decreasing the probability that such attacks would go undetected in the larger satellite population. Once such attacks were detected countermeasures could be devised and implemented by STS launched repair crews. Thus, in selection of the storage orbit a tradeoff must be made between ASAT and covert degradation vulnerabilities. That tradeoff is very much mission dependent and must be made case by case with regard to the attacker's objectives, strategy, ASAT capabilities, and knowledge of specific U.S. system vulnerabilities. However, pooling of satellites in STS-accessible (but more ASAT-vulnerable) orbits would provide some safety in numbers and present the defense with new options, such as the possibility of cover, deception, and decoy schemes for countering ASAT and covert degradation threats.

There is still the option of placing the spacecraft directly into mission orbit in both the proto-flight and operational phases. ASAT attack would then be more difficult (the space programs we are emphasizing in this study would often be put in synchronous orbit, or at least in orbits too high to be *recovered* by the STS) and would require more time. The proliferation features of the bunched launch could remain important, as could cover, deception, and decoy schemes. Finally, one option for exploiting the cost savings inherent in bunching is to be able to afford additional means for making spacecraft systems more survivable.

Implications

The key aspect of bunching we emphasize is that it affords a means for minimizing the costs of maintaining a high system availability and a low maximum expected outage period. However, depending on the specific satellite program, some aspects of bunching may not be favorable.

IV. BUNCHED LAUNCH, BUNCHED PROCUREMENT--ROLE OF FUNDING PRACTICES

THE PROBLEM

Bunching appears to have a number of attractive operational features and implementation possibilities. These have a considerable intrinsic worth (e.g., reduction of outages) or a substantial convenience element (e.g., no longer having to schedule the space system operation in detail by complex computer programs, because we need only to calculate the probable number of mission necessary spacecraft, which we can do by simple rules). Large cost savings are also generally associated with the bunching concept.

Overall, then, bunching appears to have interesting and significant payoffs. But in bunching we would purchase a lifetime (multi-year) quantity of satellites (and launch vehicles or launch services), so the usual practice of appropriating funds in annual increments poses questions affecting any effective implementation of a bunching policy. Our problem is to see to what extent a bunching policy could be accommodated, perhaps within an *existing* legal and regulatory framework and within institutional constraints prevalent in acquisition issues.

MULTI-YEAR ASSURANCES

The multi-year action to be considered here is distinct from the concept usually associated with such terms as *multi-year funding* and *no-year funding.* As most often used, those terms refer to the duration of availability (for obligation) of appropriated funds. *No-year funds* remain available until spent, and *multi-year funds* remain available for obligation for a certain number of years, after which time they revert to the U.S. Treasury. The multi-year action (*or multi-year assurance*) considered here refers to the practice of buying (or contracting to buy) multi-year quantities. When involving RDT&E funds, the practice is known as *forward financing* and is allowed only in special circumstances. There are three basic variations of this process:

1. *Multi-year procurement*: A contract for performance (production or delivery) spanning multiple years with funding appropriated in annual increments.
2. *Outset funding*: A contract for performance (production or delivery) spanning multiple years with funding appropriated *in toto* at the initiation of the contract.
3. *Outset funding/stockpiling*: A contract that can be fully performed within one year but fulfills the needs of more than one year, with funding appropriated *in toto* during the year of performance. (This concept is similar to stockpiling.)

These three variations are summarized in Table 8. Variations 1 and 2 are of direct relevance, with Variation 2 probably of highest interest for bunching.

Table 8

MULTI-YEAR ASSURANCES: WAYS TO BUY MULTI-YEAR QUANTITIES

	Performance (contract length)		Appropriations	
Variation	Single Year	Multi-Year	Annual Increments	*In Toto* at Initiation
1. Multi-Year Procurement		X	X	
2. Outset Funding		X		X
3. Outset Funding/ Stockpiling	X			X

THE AIR FORCE ROLE

Variation 1 (Multi-Year Procurement)

The Defense Acquisition Regulation (DAR) permits the execution of a contract for known requirements even if the total funds to be obligated by the contract are not then available. If the contract award is made on a multi-year basis, funds are obligated only for the first year's quantity, with succeeding years' quantities funded annually thereafter. In the event funds are not available to support a succeeding year's quantities, the contract is canceled. The contractor is protected against loss resulting from cancellation by contract provisions allowing reimbursement of unrecovered nonrecurring costs included in prices for canceled items.

From the perspective of the Air Force, this provision seems of limited use for Variation 1 on any significant scale. The Air Force cannot use this provision if the cancellation ceiling (in the contract) exceeds $5 million unless the Congress approves the cancellation ceiling by statute in advance. This limitation makes this ASPR provision inapplicable to large or even moderate-size procurements.

Variation 2 (Outset Funding)

For procurement funds,[1] there is no statutory or regulatory bar to appropriating funds covering more than a year's needs. This is not true of RDT&E funds, which are appropriated for specific increments of work to be accomplished during the fiscal year for which the funds are approved.[2] Variation 2 appropriates total funds at the initiation of a program.

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[1] These represent purchase of weapons, training devices, support equipment, munitions, vehicular equipment, communications and electronic equipment, and other organizational and base support equipment. Purchase of weapons includes provisions for fabrication of the system, modification, some component improvement, initial spares and repair parts, replenishment spares and repair costs, war consumables, technical data, etc.

[2] *USAF Budget Guidance Manual*, AFM 172-1(c3), Vol. I (Policies and Procedures), Ch. 14, Para. 6. An exception to this policy, known as "forward financing," is allowed in a very limited set of circumstances. *Ibid*., DODI 7220.24, §V(E)(6); AFR 177-13.

One Department of Defense Directive[3] explicitly allows procurement of some items before the fiscal year in which they are actually to be used. Known as *advance procurement*, this is restricted to the procurement of long lead time items. It is of limited relevance to Variation 2. Nevertheless, there is no statutory or regulatory guidance on the general question of *procurement* (cf. RDT&E) of multi-year quantities with total funding at the outset. The failure to do so appears to stem from practice rather than prohibition. The crucial stumbling block is the availability of funds from the Congress.

THE CONTRACTOR ROLE

How can a prime contractor relieve a subcontractor's or a supplier's uncertainty by making a multi-year commitment, and what risks are incurred in doing so? The DAR "Multi-Year Subcontract" section encourages prime contractors to employ multi-year subcontracting selectively and only when

1. The subcontract item is of stable design and specification;
2. The quantity required is known and firm;
3. Effective competition is assured; and
4. Multi-year subcontracts can reasonably be expected to reduce prices.

It states that "the prime contractor is adequately protected against cancellation since appropriate cancellation charges for such multi-year subcontracts are included within the cancellation charge of the multi-year prime contract." The risk of cancellation of such a subcontract (liability for unrecovered nonrecurring costs is apparently shouldered by the government instead of the prime contractor only when (1) the prime contract is canceled (and not, for example, when design changes in the system obviate the need for the item), and (2) the subcontract adheres to the four requirements listed above.

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[3] DODD 7200.4, Section III(B), implemented by the Air Force in AFR 172-14.

In most situations, prime contractors choose *not* to enter into multi-year contracts with their subcontractors or suppliers, even should quantity price breaks be available (multi-year subcontracts are clearly the exception rather than the rule). This occurs when the uncovered risks outweigh the possible gains.

SOME POSSIBLE POLICY IMPLICATIONS RE MULTI-YEAR ASSURANCES

The legal and regulatory framework for making multi-year assurances seems insufficiently responsive to some of the problems and reforms called for in a shift away from annual, incremental funding. Possible policy responses aimed at enhancing its responsiveness are:

- Variation 2 (outset funding):

  New uses for advance procurement (other than for long lead time items) could be permitted.

  The policy on *procurement* of multi-year quantities could be clarified.

- Multi-year commitments by prime contractors:

  Protection for prime contractors entering into multi-year subcontracts could be extended by (1) providing coverage of subcontractor cancellation charges despite noncancellation of the prime contract and (2) allowing multi-year subcontracts to be used to retain a participating subcontractor in a program.

The absence of an express authorization or prohibition conditions use of each funding arrangement on the provision of funds by the Congress. An immediate response by the Air Force could be to discuss with the Congress its needs and the benefits of multi-year assurances. The Congress would require persuasion that such actions need not involve their forfeiture of oversight and control.

In these conditions, a bunching policy could be carried out. A number of variants of a relation between bunching and funding practices are possible. For example, in the proto-flight concept, normal competitive RDT&E could be used. The winner of that RDT&E competition

might then avail itself of the procurement provisions of Variation 2, using at that time the stable design of the spacecraft that was presumably validated by the proto-flight phase.[4] This procedure would accommodate to the general constraints placed on RDT&E programs while capitalizing on the production possibilities inherent in outset funding.

The Nature of the Programs Conducted Under Bunching Concepts

The bunched procurement would involve stable, high quality, fully developed articles; would emphasize major follow-on developments leading to new generation systems as the means for introducing major new technology into the space programs; would exploit intensive test-launch-test sequences; and would compress the time involvement of SPOs and contractors.

The test-launch-test sequence would be particularly important and could be done through several representative options.

1. Accelerate the first article, subject it to test-launch-orbital test. Any changes found necessary would be made in articles already on the production line.
2. Test-launch-orbital test the proto-flight article. If that test sequence is successful, use the proto-flight article as the stable, proven design that is *then* committed to production.
3. Hold a proto-flight competition, with several contractors, and with the intensive test-launch-orbital test sequence. Commit to production the article that *wins* the proto-flight competition. Such a competition would be more expensive than the usual methods for contractor selection, but, as one possibility, the necessary funding could be provided by part of

[4] Because the proto-flight spacecraft is a fully developed, well-defined design, it would be possible *in principle* to award the production contract to the contractor judged best able to *produce* the spacecraft. That contractor need not necessarily be the winner of the RDT&E competition. See the discussion of contractor competition in M. D. Rich, *Competition in the Acquisition of Major Weapon Systems: Legislative Perspectives*, R-2058-PR, November 1976.

the anticipated net savings from the bunching concept. Competition would be enhanced by this option.

Even though we can make a persuasive case that, for operational and cost savings reasons, the notion of bunched launch and bunched procurement merits serious consideration as an attractive alternative acquisition strategy option, we would be remiss in not recognizing that a number of problems can arise in carrying out such an option. These problems are mainly institutional, as are most of the problems surrounding acquisition difficulties.

The notion of multi-year commitments through annual incremental funding is a case in point. There is no statutory or regulatory bar to implementing outset funding appropriated at the initiation of the production program for multiple year production. But it would be difficult to persuade the Congress that this process did not vitiate its responsibilities for monitoring and validating expenditures, and for reviewing the balance between program needs and available funds. Nor would it be easy to convince decisionmakers that the combination of protoflight RDT&E, phased acquisition, and outset funding for production is the most effective and productive way for acquisition strategies to develop, for the kinds of space programs we have emphasized.

Many contractors would also find bunching concepts and the associated acquisition strategies to be different from and perhaps less congenial than their accustomed way of doing business. The shorter time involvement of a contractor in the program and the elimination of the continual modifications and changes over the whole program would remove one of the ways some contractors spread and adjust their work load. Contractors use this cushion to maintain program continuity and to provide some funding flow during the entire program duration.

An objection to the bunching notion has also been raised because of the "sawtooth" pattern of work a given contractor in a given program would have when the compressed bunched procurement phase was followed by a bunched launch. The argument is that this would seriously perturb a contractor's manning flexibility and his capability to make a transition between programs. It is difficult to evaluate the merits

of such concerns. Adoption of bunching would, in principle, permit more space programs to be conducted, thus raising the number of opportunities for a contractor to become engaged in space developments. Many contractors use their most skilled and capable personnel mainly in proposal efforts and in the early RDT&E phases of programs anyway, leaving production and execution of the bulk of the program to other personnel teams. Bunched procurement is in this sense an explicit accommodation to practice.

There is little doubt that to carry out bunching concepts effectively will place demanding and in some cases novel planning requirements on both SPOs and contractors. We believe such planning requirements are fully within the capabilities of SPOs and contractors to meet and that such requirements can be met if the prospective benefits of bunching adequately motivate program sponsors and associated contractors. There have been successful programs that used at least some of the aspects of bunching discussed here.

V. CONCLUDING REMARKS AND RECOMMENDATIONS

High spacecraft reliability during orbital operation, and hence long MMDs, can significantly reduce the total buy of spacecraft required to support a given mission for a given time. This conclusion applies to any acquisition strategy.

Very high reliability of spacecraft is possible during a dormant, or partially energized, level of operation, suggesting a bunched launch, at least for an important class of space programs. In a bunched launch system, all mission-required spacecraft are put into orbit as promptly as possible. Those spacecraft not needed in the earlier portions of the mission are stored in a dormant state in orbit and are turned on for operational use when predecessor spacecraft fail, thus avoiding outage times associated with replenishment from ground launch.

The bunched launch concept permits very high average system availability (unity) without the costs of a substantial number of extra spacecraft that would be required for high system availability by continuous replenishment from ground launches. This is true even when the latter strategy continually stores and replenishes sufficient spares in orbit for a comparably high system availability.

For space missions where high availability is a requirement, the bunched launch approach provides a significantly less costly way to ensure high system availability than alternative strategies normally considered. The bunched launch approach implies a compressed, or bunched, procurement period that makes possible still further cost savings (other than those resulting from the lower number of spacecraft required in the bunched launch to achieve high system availability). These further cost savings result from such factors as a higher learning rate in intensive, stable production over the rate of most spacecraft acquisition programs and a compressed program management time. There may be other beneficial effects such as opportunities for more efficient use of and better scheduling of skilled RDT&E manpower and other critical resources.

The cost implications of those effects we have considered are sensitive to scenario and assumption to some degree. We therefore present an example, noting that both more and less dramatic cases can occur.

In Sec. I, 13 spacecraft were required to achieve a system availability of unity for a bunched launch and 20 for a conventional launch with two continually replenished spares in orbit. In Fig. 6 we have shown derived program and launch schedules and funding profiles for these cases.

For the bunched case the production rate is three or four spacecraft per year, for the normal procurement one or two per year; in addition, the spacecraft in the bunched case are assumed identical to the proto-flight article. We have therefore used a learning curve slope in the bunched case, after correcting for inflation, such that the 13 spacecraft cost \$325 million. The 13 launchers for this case are assumed to cost 13 × 25, or \$325 million, so that the total program

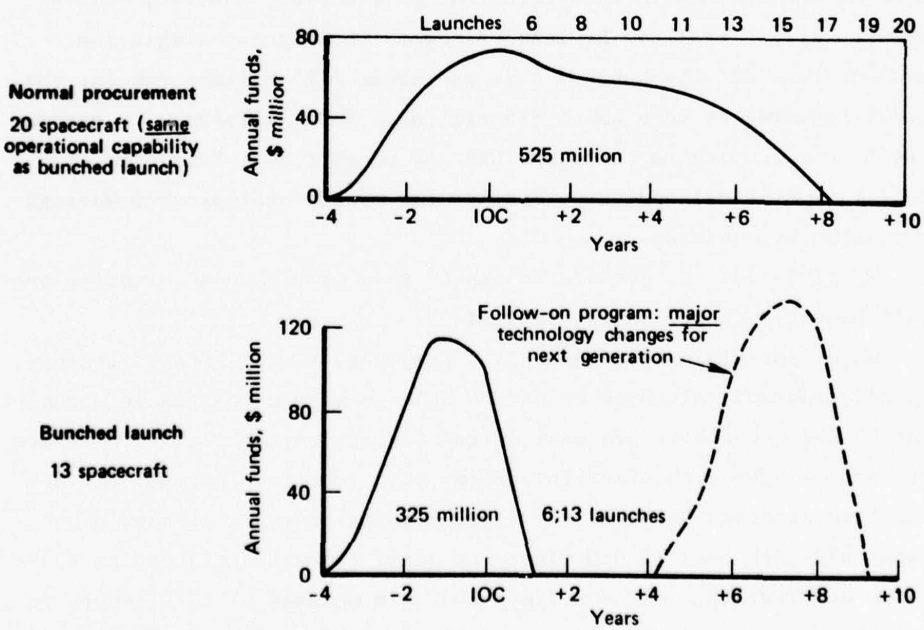


Fig. 6—Funding profiles for normal and bunched procurement

cost is \$650 million. For the normal procurement we assume a less effective learning curve slope (but still less than 100 percent) to produce a cost for the 20 spacecraft of \$525 million. With the seven additional launchers costing \$175 million, the basic program costs for the normal procurement would be \$1025 million. Counting the additional out-year inflation costs and additional program management costs could add another \$125 million, to make the normal procurement strategy cost \$1150 million, \$500 million (or $\sim$ 80 percent) more than the bunched case. Some parts of these estimates might be regarded as softer than others, so we can establish a hard, certain component of the estimates by simply ignoring the procurement-related effects of differential learning curves, inflation effects, and program management costs and just consider the basic cost of seven additional spacecraft and launchers implied for the same system availability in the normal procurement case. This gives 7(35 + 25) or \$420 million as the added cost of the normal procurement.

By either method of estimation, the bunching concept achieves substantial net savings in this illustrative example. However, Fig. 6 shows an effect that may be less welcome. The highest single year funding peaks for the bunched case are about \$115 million and for the normal procurement case about \$75 million. This difference in maximum single year funding may make the bunched concept more "visible" and subject to critical analysis, despite the great total program savings achievable by bunching.

We capsulize the considerations of this report on alternative spacecraft acquisition strategies in Table 9.

We do not claim that there is a dominant, single "best" strategy for all programs, although we may be able to make a reasonable argument that bunching concepts are well suited for at least the class of space programs we have emphasized throughout this report. Whatever the acquisition strategy selected for a given space program, it should be compatible with overall DoD plans for acquisition techniques, as these evolve and develop. But certainly the main message of this report is that the tradeoffs implied by the following matrix should be faced and evaluated.

Table 9

TYPICAL ARGUMENTS MATRIX

Strategy	Pro	Con
"Bunched" (single buy, all stored in orbit) One bunch Two bunch	Lowest costs (total) Optimal availability Major technology advances Transfer to users Outset funds case Spares allocation Maintain competition Minimal scheduling	Institutional changes Peak funding Demanding planning Concerns: Fear of failure Responsiveness Orbital management (STS; two-bunch) Biggest payoffs: Large constellations, long program
Stretched buy, and/or stretched launch (spares possible)	Incremental technology advances Adaptive planning Institutional familiarity Low peak funding Lengthy R&D period	Inhibit new systems Higher cost (total) Inhibit operational transfer No case for outset funds Counterproductive R&D Scheduling

A POSSIBLE NEXT STEP

The Air Force should select one or several prospective 1980s space programs and review in depth the pros and cons of adopting the kinds of acquisition strategy elements discussed in this report. The review should consider the development of arguments for persuading the Congress to allow the Air Force greater freedom in funding important systems acquisitions, using the selected space programs as explicit cases.

Appendix A

COMPUTER SIMULATION MODELS FOR SPACE MISSION PLANNING

CAUTIONARY NOTE

This report takes a rather cautious view of the applicability of computer models for detailed space mission planning. Much of this caution is due to the ways reliability has been modeled in such simulations, particularly in the use of the associated MMDs.

Low MMDs have sometimes been justified as "conservatism" in spacecraft procurement, presumably reflecting our uncertainty in achieving long spacecraft lifetimes. But certain contractor teams, working in concert with certain SPOs, have used design, development, testing, and command/control practices that result in long spacecraft lifetimes. The extent to which this can be universally achieved is a subject worthy of further study. It is also a subject of considerable institutional sensitivity.

Second, computer simulation programs modeling satellite replenishment schedules, the total number of satellites needed for a given mission, etc. appear, on occasion, to have been used by prescribing the outputs and ascertaining the inputs needed to obtain them. A more demanding and complex problem is to design computer models to prescribe and optimize general acquisition strategies in the presence of fiscal and operational constraints. In our judgment, there is no entirely adequate model of this sort, but it is not impossible to formulate one.

Our conclusion is that simulation programs should be primarily used in *comparing* alternative strategies and in a lesser role in generating absolute numbers for any given strategy. Possibly the latter cautions can be alleviated by simulations that deal more adequately with the reliability behavior we should expect. In the meantime, Rand has developed a convenient Satellite Availability Simulation Program (SASP) to provide the comparative insights we need to weigh alternative acquisition strategies.

WHAT SASP DOES

SASP simulates satellite system operation over long periods of time using the Monte Carlo technique of repeated trials. For each trial, random numbers and the user specified reliability function determine satellite lifetimes, system failures, and replacement satellite needs. After repeated trials, statistical results are computed and printed: e.g., probability of need for each satellite, average system availability, and system point availability. There are several other computer programs for such analyses (Aerospace GAP, etc.); the present program was prepared to enable prompt, easy comparisons for Rand staff.

SASP outputs can be used to investigate effects of the following factors on satellite/launcher need times and availability:

1. Variations in the satellite reliability function.
2. Variations in launcher reliability and probability of successful satellite initialization in orbit.
3. Variations in launch schedule.
4. Previous history of launcher success and failure.
5. Block change or major changes in satellite reliability characteristics.
6. Nonrandom spacecraft failure rates (e.g., failures produced by wearout phenomena).

In connection with item 6, there is a growing body of evidence that spacecraft failures do not all occur randomly and, for sufficiently tested space systems, may occur infrequently. As a first step, for estimating effects of nonrandom failure rates, SASP is capable of investigating a range of assumptions of assumptions about the relative importance of random piece-part failure phenomena vs. wearout phenomena.

SASP OVERVIEW

The simplest way to demonstrate the structure and scope of SASP is to list major program inputs and outputs.

Inputs for SASP are as follows:

INCASES	The number of cases to be included in a single run.
MCI	Number of Monte Carlo iterations (M.C.I.).
IS	The total number of satellites.
N	The total number of stations--the number of operating mission satellites to be maintained in orbit for the life of the satellite project. (Does not include on-orbit spares.)
M	Total project lifetime in months.
IDD	Launch response time. Minimum time to replace a failed satellite.
IGEN	Number of satellite generations (only 1 or 2 allowed).
R	Launcher or booster reliability--probability of successful launcher operation.
SINIT	Satellite initialization reliability--probability that the satellite will be successfully placed into correct orbit and into a proper operational configuration.
ALPI, BETAL	Reliability function parameters for first generation satellites.
ALPWO, BETAWO	Wearout function parameters for first generation satellites.
PX	Percent of time wearout function dominates piece-part reliability function. (PX = 0 unless user wants to test alternative hypotheses about the validity of piece-part reliability functions, in which case $0 < PX \le 1$).
ALP2, BETA2[1]	Reliability function parameters for second generation satellites.
ALPWI, BETAWI	Wearout function parameters for second generation satellites.

[1]Note: If IGEN = 1--i.e., only one generation of satellites is involved--ALP2, BETA2, ALPI, BETAWI, and MGEN are not input.

MGEN	Month in which the second generation of satellites becomes available.
ID(J)	Month in which Jth satellite station is scheduled to be operational.
IAV(IS)	Month in which the ISth satellite/launcher is available for launch.
NDETER	The number of launches treated deterministically rather than randomly in the run.
IDETER(ND)	1 if NDth deterministic launch was a success, 0 if a failure.
NP	The number of fixed probability of need values to use in estimating satellite/launcher availability schedule.
SET(NP)	The values of probability of need for which satellite/launcher availability will be printed out.

To *update* satellite/launcher requirements for a given space project, one can input historical data on launcher successes or failures for launches attempted in the past and exempt these specific launches from the probabilistic treatment provided in the program. The variables NDETER and DETER(ND) provide this capability in the SASP program.

Weibull distribution functions are used to represent satellite reliability characteristics, for both wearout phenomena and random piece-part failure phenomena. The selection of the Weibull is a matter of convenience; the user may insert a different form of the reliability function if he wishes.

The Weibull reliability function is given by the expression:

$$R(t) = \exp\left[-(t/\alpha)^{\beta}\right] .$$

R(t) is the probability of successful operation to time t, and α and β are parameters to be estimated.

Variables in the SASP output are:

AVOUT	Expected length of system outage, where a system outage occurs any time the number of operating satellites is less than the number of stations, N.
AVNUM	Expected number of outages occurring during the project lifetime, M.
TOTOUT	Expected total outage time over the lifetime of the project.
AVMAX	Expected maximum outage.
PSHORT	Expected probability that the system will be operational at the end of the project life.
AVPT	Point availability of the system.
RDIST(K)	Distribution of time at which the kth satellite is needed.
P(month)	Probability of need for each satellite.
IPN(IS,PN)	Satellite/Launcher availability schedule associated with probability of need level PN.

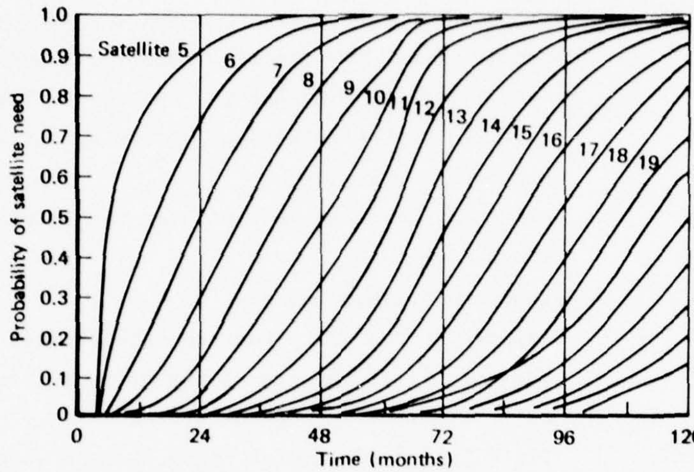
In addition, a number of derivative outputs can be formulated.

A SAMPLE OF SASP RESULTS

The combinatorial number of cases with which one could illustrate SASP is obviously enormous, so here we present a very few results exhibiting specific points. The preceding sections contain other SASP calculations. We have also discussed situations in which the need for some of the more detailed scheduling outputs from SASP (or other computer programs) can be obviated.

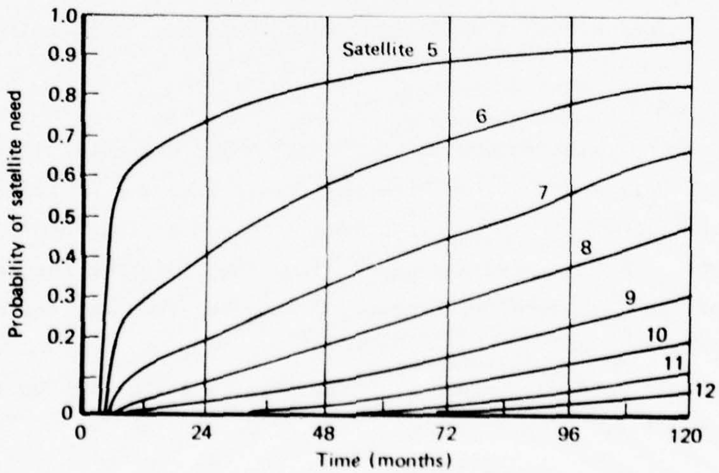
The sample data inputs and illustrative results are shown in Figs. A.1, A.2, and A.3.

1. Figures A.1 and A.2 show the large effect the Mean Mission Duration (MMD) has on spacecraft need schedules. The plots are conventionally interpreted. In Fig. A.1 there is a 10 percent chance ($P_N = 0.10$) that the 10th satellite will be needed by month 27, a 50 percent chance ($P_N = 0.50$) that it will be needed by month 48, and a 90 percent chance (that is,



Number of stations = 4	Number of satellites = 25
Station starting time = 0, 2, 4, 6 months	Satellite wearout = 60 months
Booster reliability = 0.87	Mean mission duration = 30 months
Launch response time = 2 months	Weibull function, $R = \mathrm{Exp}-(t/37.91)^{1.39}$
S/C initialization = 0.94	Iterations = 1000

Fig. A.1 — Base case, 30 month MMD

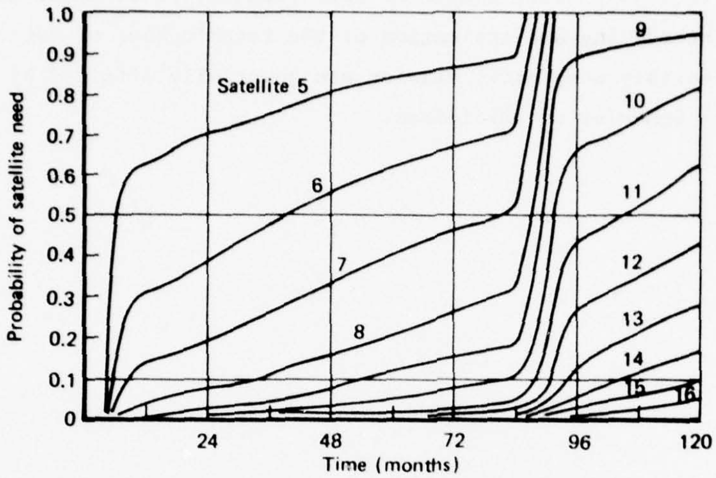


Number of stations = 4	Number of satellites = 12
Station starting time = 0, 2, 4, 6 months	Satellite wearout = 120 months
Booster reliability = 0.87	Mean mission duration = 90 months
Launch response time = 2 months	Weibull function, $R = \mathrm{Exp}-(t/232)^{0.86}$
S/C initialization = 0.94	Iterations = 1000

4 (b) — Perturbation, 90 month MMD

Fig. A.2 — Comparison of computer simulation results

petitive RDT&E could be used. The winner of that RDT&E competition



Number of stations = 4
Station starting time = 0, 2, 4, 6 months
Booster reliability = 0.87
Launch response time = 2 months
S/C initialization = 0.94

Number of satellites = 16
Satellite wearout = 84 months
Mean mission duration = 65 months
Weibull function, $R = \text{Exp} - (t/232)^{0.86}$
Iterations = 1000

Fig. A.3—Perturbation, 65 month MMD

virtual certainty) that it will be needed by month 65. In Fig. A.2 there is a 10 percent chance that the 10th satellite will be needed by month 80, and its chance of being needed by the end of the mission is just under 20 percent.

2. Fig. A.3 shows the scheduling effect of a spacecraft having a wearout lifetime (84 months) significantly less than required mission duration (120 months), and an MMD of 65 months. The steep rise in P_N for many of the satellites reflects the role of the wearout period in terminating an individual satellites' operability.

In Figs. A.1, A.2, and A.3, no constraint has been considered that reflects assumptions on *launch vehicle* scheduling. Such constraints can be handled by SASP and naturally perturb the nature of the curves shown, all other parameters being equal.

RDT&E competition. See the discussion of contractor competition in M. D. Rich, *Competition in the Acquisition of Major Weapon Systems: Legislative Perspectives*, R-2058-PR, November 1976.

From this very brief sample of SASP results, it is clear that satellite scheduling and estimation of the total number of satellites needed to satisfy a specific mission are powerfully affected by the reliability behavior of satellites.

a transition between programs. It is difficult to evaluate the merits

Appendix B

SPACECRAFT COST--RELIABILITY ISSUES

DATA BASE AND METHODOLOGICAL ISSUES

Cost and reliability information were collected on 23 spacecraft programs. The cost information consists of total subsystem cost, for the number of spacecraft produced, plus AGE, spares, identified reliability costs, operations costs, and systems engineering or program management costs for the spacecraft as a whole. The reliability information consists of design lifetime and achieved lifetime, both measured in years. Table B.1 shows some of the data collected.

The spacecraft projects included NASA-funded scientific spacecraft, both earth orbital and interplanetary, and Air Force satellites. The cost data are actual costs in then-year dollars for completed programs, except for two programs.

Because recorded costs for spacecraft programs in the data base contained only standard reliability cost items (reliability, quality control, quality assurance, and safety), we needed to account for some of the hidden reliability cost items not shown in the typical cost report format. Items estimated included testing performed for reliability reasons--as contrasted to the testing for performance and design verification--and increases in expenditures for some high reliability parts purchased to improve subsystem reliability. A number of other reliability-related functions are performed that cannot, under the current means of cost reporting, ever be isolated and identified as reliability costs, including the costs for redundancy, subcontractor test, and subcontractor inspection. The data problems we encountered are summarized in Fig. B.1.

To get around such data problems in some measure, a methodology was derived based on a specific spacecraft program, using spacecraft similar to those spacecraft in the data base, but for which very detailed costs could be obtained. These costs were at a much lower level of aggregation than the costs for the rest of the spacecraft in the

Table B.1

SPACECRAFT COST AND PERFORMANCE SUMMARY

Spacecraft	Total Cost (TPC)	Reliability Cost (RC)	% RC/ TPC	Design Life (DL)	Achieved Life (AL)	S/C Weight	RC/ Pound	Year (Time)	Non-recurring Cost (NR-C)	Recurring Cost (R-C)	No. of Satellites
Pioneer A-E	85.580	15.657	18.08	.5	5.3	145.3	.108	1958	19.445	44.161	5
OGO	129.271	19.480	15.07	1.0	3.1	1230.0	.016	1964	50.131	62.450	3
VELA	49.048	12.644	25.78	.9	4.9	305.7	.041	1965	7.805	34.778	10
VELA V	30.178	6.107	20.25	1.5	4.0	522.4	.012	1969	15.678	10.444	2
Intel. SAT III	70.324	12.873	18.30	5.0	2.7	249.9	.054	1968	12.558	50.808	9
MOD 35 Phase 1	150.381	32.167	21.39	3.0	3.4	1856	.017	1967	43.528	77.291	4
Pioneer F&G	83.891	20.369	24.28	2.5	2.0	508.5	.040	1964	40.590	27.032	2
OSO	79.290	18.671	23.55	1.5		1846	.010	1967	27.176	48.264	4
HEAO	87.850	15.297	17.41	.67		5530	.028	1974	30.975	38.585	3
777	193.864	39.691	20.47	5.0	3.8	1128	.050	1972	46.101	126.360	6
MOD 35 Phase 2	165.765	50.015	30.17	3.0		2085	.024	1974	48.040	117.727	9
OSO-1	44.903	9.54	21.26	3.0		2247.6	.004	1973	21.115	12.329	1
Sync. Met. Sat.	46.306	5.314	11.50	5.0		555	.010	1972	15.433	19.384	3
OSO 3-7	65.826	18.231	27.70	.6	4.0	787	.023	1968	20.122	45.703	5
ATS F-2	30.198	5.731	19.00	3.0	2.4	750	.008	1966	22.515	7.683	1
ATS F-1, F-3	42.447	8.477	20.00	3.0	8.0	700	.012	1967	26.300	16.147	2
ATS F-4, F-5	46.216	9.825	21.30	3.0	6.0	775	.013	1968	28.106	18.110	2
ATS-F	96.247	17.562	18.30	5.0		3078	.006	1972.5	50.826	45.421	1
ERTS 1, 2	67.722	13.505	19.90	2.0	4.0	1965	.007	1971	29.156	38.566	2
Nimbus E, F	70.879	16.543	23.30	1.0	3.0	1545	.011	1971	26.920	43.959	2
ITOS M, A, B, C	37.106	5.865	15.80	1.0	1.0	686	.008	1969	17.609	19.497	4
ITOS D, E, F, G	43.362	9.191	21.70	1.0	2.3	750	.012	1971	10.557	31.805	5
Defense Met. Sat.	37.429	4.469	11.94	2.0		981	.005	1973	20.059	17.370	3

DATA PROBLEMS

Most Financial Reporting Systems Do Not Show All Reliability Costs

Three Types of Reliability Costs in Each Space Program

A. Stated Reliability Costs
   - Reliability
   - Hi-rel parts
   - QA
   - QC
   - Safety

B. Hidden Reliability Costs
   - Reliability testing
   - SRTE
   - Test documentation

C. Undeterminable Reliability Costs
   - Redundancy
   - Derated parts
   - Subcontractor reliability costs

Fig. B.1--data problems

data base. A series of ratios were constructed for each spacecraft subsystem, for both recurring and nonrecurring cost categories, to estimate the percentage of hidden reliability cost for the recurring or nonrecurring total subsystem cost. These percentages are applied to the subsystem costs for all the spacecraft, added to the stated reliability costs, and then summed to determine reliability cost factors.

GENERAL FINDINGS

To determine the reliability-cost relationship for spacecraft, the data gathered on 23 spacecraft programs were adjusted to account for certain costs--mainly for reliability testing--that are not normally reported as reliability costs. The resulting costs were then normalized to the total program costs to find the percentage of total program cost attributable to reliability. When these relative costs were regressed, through a great many regression analyses, against other variables such as the designed or achieved lifetimes, the results were quite surprising: They indicate a very weak relationship (or none)

between the resources committed to the reliability and the reliability proxies, the lifetimes of the systems. The proportionate reliability costs were also a very weak function of the complexity or size of the spacecraft. What is done within the scope of the reliability program is of course important; see the remarks on integrated or acceptance testing in Sec. II.

How can this phenomenon be explained? One reason is that there are, and probably always will be, problems with the data because there are three classes of reliability related costs: those stated explicitly, those that can be inferred from examples of disaggregated data (the hidden reliability costs), and those that cannot be determined at all because they are incorporated in other costs. The predominant example of this last type is the redundancy effort included under design and engineering.

A second explanation for the lack of a strong relationship between reliability cost and designed or achieved reliability is that institutional procedures, as defined by the MIL SPEC (military specifications or their NASA equivalents) and the various test programs specified by the contractors and using agencies, are so comprehensive that many potential sources of unreliability are eliminated before the first launch of a spacecraft.

Our discussions with contractors inevitably resulted in our asking the question, "What would you do differently for a five-year satellite than you would for a one-year satellite?" The answer was: "Almost nothing, except for the use of more high reliability parts and added redundancy; the test program, MIL SPECs, and performance verification would probably be much the same."

Some samples of these extensive cost investigations are shown in Figs. B.2 and B.3. Figure B.2 plots the reliability cost as a percentage of the total program cost against achieved life in years. The chart includes programs in which the spacecraft are very complex. Despite this, the fractional reliability cost is of the order of 1/5 or 1/4 of the total program cost, even for very long achieved lifetimes. There is an extremely weak overall dependence of achieved lifetime on costs attributable to realization of that lifetime. One possible

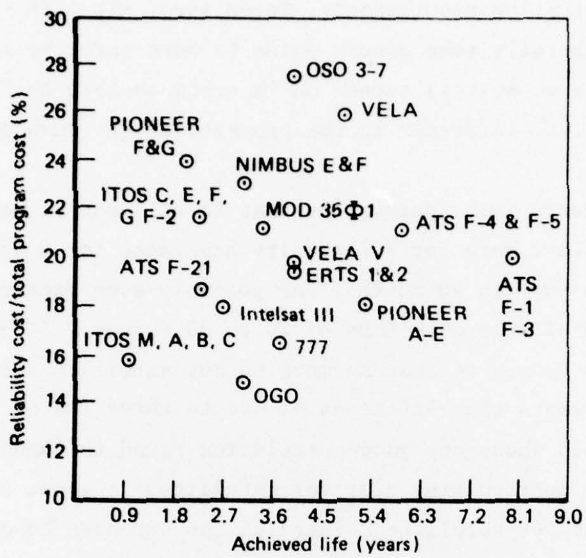


Fig. B.2 — Reliability cost as a percent of total program cost versus achieved life

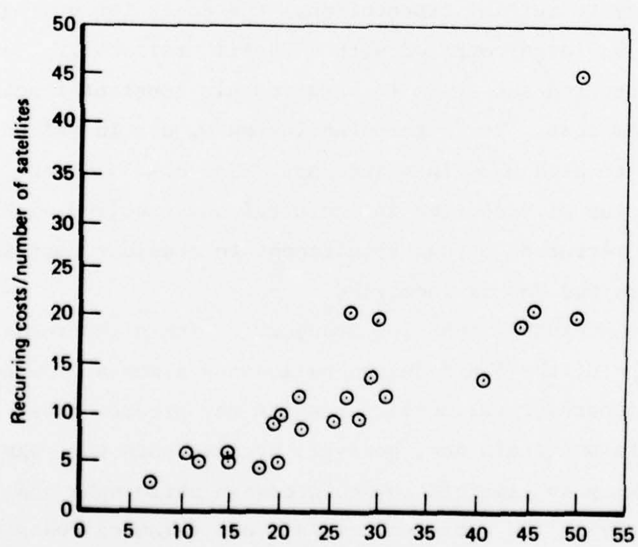


Fig. B.3— Recurring cost/number of satellites versus nonrecurring cost

explanation is that a competent contractor, by his own initiative and as guided by testing requirements, incentives, MIL SPEC requirements, etc., will generally take enough pains to make sure the satellite functions properly when it is turned on in orbit so that he "automatically" buys long orbital lifetimes in the process, if the turn-on is successful at all.

The evidence seems persuasive that it will not be necessary to pay much, if any, more for reliability assurance for a satellite with MMDs of 60 to perhaps 90 months, and possibly even greater MMDs, contrasted to satellites with MMDs of 20 to 30 months. In a historical sense, it has seemed to cost no more to buy satellite lifetimes of four to nine years than lifetimes of one to three years.

Figure B.3 shows one good correlation found through the regression analyses--the nonrecurring cost for satellites is about 2.5 times the recurring cost per satellite. That is, the R&D cost to develop a spacecraft is about 2.5 times the unit cost of a developed satellite. We use this relation to estimate the R&D cost associated with the spacecraft used in some of our examples.

Our major conclusion on the cost-reliability issues is that (somewhat contrary to initial expectations) the costs for buying added life seem not to be large compared with a "basic" reliability cost that must always be incurred and seems to be a roughly constant fraction of the total program cost. It is this conclusion we use in validating the payoffs due to high MMDs in spacecraft. The cost minimization brought about by virtue of reduction in the total buy required as MMDs increase is scarcely perturbed by any requirement to consider cost increases per spacecraft as the MMD is increased.

It is conceivable that for spacecraft within the recovery and repair envelope of the STS a design philosophy aimed at low cost and acceptance of whatever reliability results may produce other cost minima. This is quite uncertain now, however, because both the magnitude of the cost savings by an explicit low cost design philosophy and the associated STS recovery and subsequent repair and relaunch costs cannot be estimated today with any confidence.

Appendix C

WORK-AROUNDS

The ingenious activities of satellite designers, managers, and system controllers in correcting satellite malfunctions and anomalies that would otherwise result in satellite failure are not represented in current satellite replenishment models. In a preliminary way we have explored the effect of this omission on various measures of system performance and have developed analytical methods for incorporating work-arounds in current replenishment models. Doing so significantly improves system performance and lowers procurement requirements. A more definitive study is now being conducted to provide program managers with the data they need to include the effect of work-arounds in their replenishment studies.

Incorporating the effect of work-arounds into the lifetime number generator in current satellite replenishment models is quite easy. Each time such a number is required in the simulation, a two-step procedure is followed:

Step 1. Simulate the number of work-arounds, N_w, the satellite will experience.

Step 2. Generate $N_w + 1$ random numbers from a uniform [0,1] distribution, form the product, and use the result to generate the lifetime number of the satellite.

This approach requires that a probability distribution, P(n), for the number, n, of work-arounds be input into the replenishment model. Given P(n), this procedure is easy to incorporate into existing satellite replenishment models.

A Poisson distribution could be assumed for modeling Step 1 above; the probability of any given number, n, of work-arounds for any satellite is given by:

$$P(n) = \frac{\lambda^n e^{-\lambda}}{n!}, \quad n = 0, 1, \ldots, \infty \qquad (1)$$

where λ is the average number of work-arounds per satellite. This is a simplifying assumption requiring only the estimation of the parameter λ, rather than the estimation of P(n) for every value of n in the absence of such an assumption. One would expect to find some deviation from the Poisson because of the upper limit on the number of work-arounds per satellite, which would inflate the value of P(0) and reduce the value of P(n) to zero for values of n greater than this upper limit. For values of λ derived later, this deviation is insignificant.

A high confidence estimate of the work-around distribution, P(n), $n = 0, 1, \ldots N_{max}$, should be derived from a comprehensive review of U.S. satellite experience. Lacking this, we can obtain a preliminary estimate of λ for the Poisson distribution just assumed. This estimate is derived from a small sample data base consisting of ten programs, including 25 satellites for a total of 50.9 orbit years, as shown in Table C.1. Of the 35 major anomalies shown, 18 meet our criteria for work-arounds. For this sample there are 18 work-arounds for 35 satellite orbit years, or for 25 satellites. The Poisson parameter for this small sample is therefore estimated to be:

$$\hat{\lambda} = 18/(611/12) = 0.35 \text{ work-arounds per orbit year, or}$$

$$\hat{\lambda} = 18/25 = 0.72 \text{ work-arounds per satellite.}$$

Using this estimate for λ in the subsequent discussion shows that improvements in *effective* MMD of the order of 50 percent can occur (see Table C.1).

What precisely is a work-around? Obviously it refers to activities and procedures the effects of which are not captured by the reliability function. We intend that the following definition of work-around be used:

The ingenious activities of satellite designers, system managers, and system controllers in compensating for any satellite malfunction,

Table C.1

PROGRAM DATA FOR EVALUATION OF PROGRAM SUCCESS

Program	DSCS-II				DSP, Phase I				STP (S3)			STP P72-1	SMS			ITOS		OSO	Nimbus E/F		ATS F	Pioneer		STP 7f-2
Flight Number	1	2	3	4	1	2	3	4	1	2	3	1	1	2	3	1	A	8	5	6	6	10	11	1
Anomalies																								
Major	5	7	1	1	5	2	0	1	1	0	1	0	2	0	1	1	2	1	0	0	2	0	0	2
Weighted	1.43				0.37				0.65			0	0.58			1.20		0.83	0		0.93	0		0.78
Failure	1	1	1	0	1	0	0	0	0	0		0	0	0	0	1	1	0	0	0	0	0	0	0
Report period (months)	(a) 19.0	(a) 10.1	(a) 32.4	36.6	(a) 40.1	69.9	60.8	45.5	6.8	18.0	6.0	18	(d) 19.7	19.8	12.0	(a) 16.8	(a) 8.3	12	51.6	21.0	21	34.5	26.3	(a) 25.6
Mission life (months)	60				36				6			12	60			12		12	12		60	60		6
Spacecraft delivered																								
Actual	4				4				3			1	3			8		1	2		1.6	2		1
Planned	4				3				3			1	2			4		4[c]	2		2	2		1
Schedule (month)[b]																								
Actual	33				55				21			18	60			33		49	32		45	27		18.6
Planned	23				42				17			15	30			25		32	32		31	27		17.8

SOURCE: "Standardization and Program Practice Analysis--Final Report," Aerospace Corporation Report No. ATR-77(7353-01)-1, Vol. II, March 1977.

[a] Time to flight failure or termination.

[b] Time to first launch.

[c] Includes a prototype. This was changed to only a protoflight.

[d] Spacecraft placed in standby on 9 January 1976 and reported to be satisfactory four months later in standby mode.

anomaly, or part failure that would result in failure or severe degradation of mission accomplishment.

- o Excludes anything that can be corrected by switch-over to redundant units or backup modes of operation captured in the satellite reliability function.
- o Excludes anything associated with "infant mortalities"--satellite failures during the first six months of operation.
- o Includes procedural and software changes not captured in the satellite reliability function.
- o Includes malfunctions, anomalies, and parts failures that have minor effects on mission accomplishment but may significantly affect the wearout characteristics of the system.

Work-arounds are not without costs. Because they involve software and procedural changes, they affect support requirements placed by the SPO on the Satellite Control Facility. The capacity of the Satellite Control Facility to service the work-around requirements of a growing satellite population in the next decade may provide the ultimate limit on the work-around distribution, $P(n)$.

A good estimate of the effect of work-arounds on system procurement and system performance requires the use of computer replenishment models. Rand's Satellite Availability Simulation Model has been modified to incorporate the necessary changes; the effect of incorporating work-arounds of course depends on the assumed value of the Poisson parameter, λ. Figure C.1 illustrates the effect of work-arounds on various measures of system performance with λ as a parameter, using reliability estimates relevant to Program A. As expected, system performance in every category is improved when the effect of work-arounds is included. The improvement in estimated system performance is due to differences in system outage time that result from work-around activity in contrast to those resulting from ground launch of a replacement satellite in addition to the added life of the satellite made possible by work-arounds. The expected improvement for a nominal 13 satellite system is summarized in Table C.2, as a function of the average number of

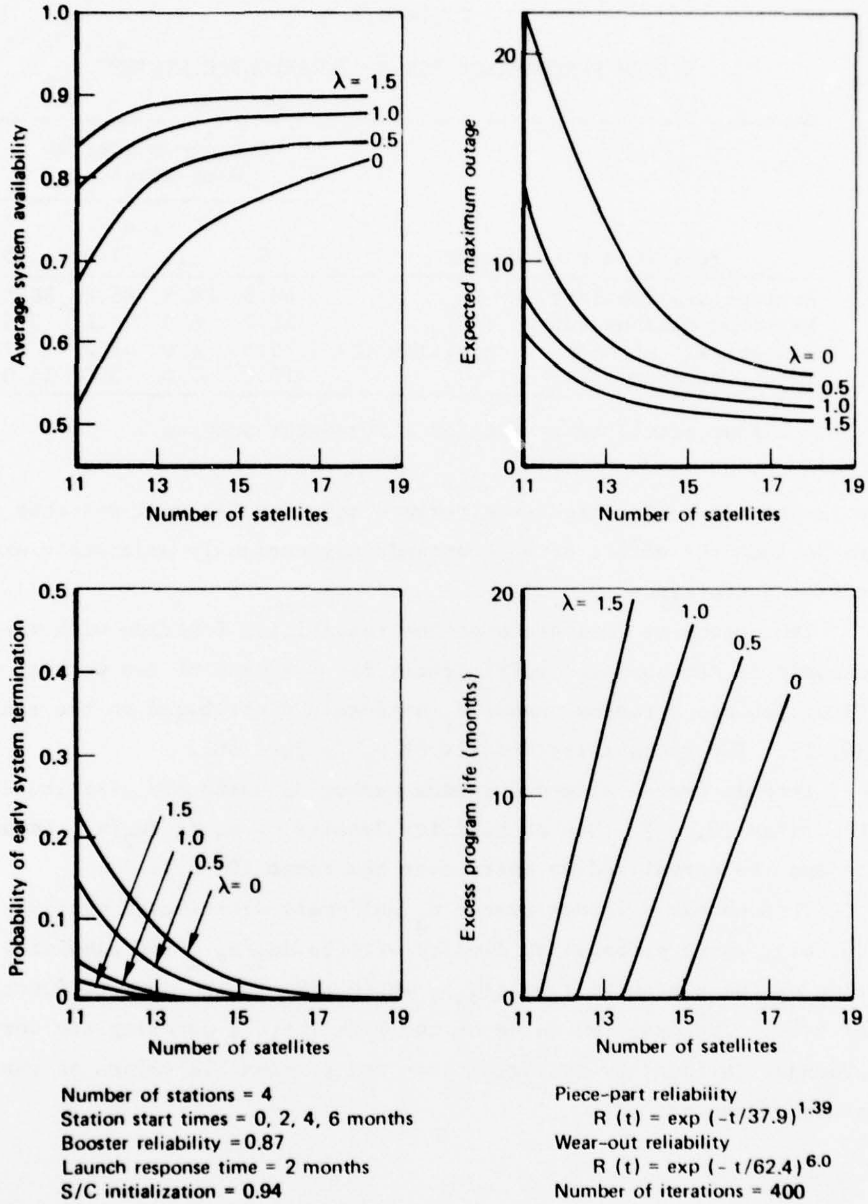


Fig. C.1--The effect of the average number of work-arounds (λ) on system performance, for a 60-month program

Table C.2

SYSTEM PERFORMANCE FOR A 13-SATELLITE SYSTEM[a]

Performance Parameter	Average Number of Work-Arounds λ = 0	.5	1.0	1.5
Average availability (%)	68.5	80.5	85.0	88.5
Expected maximum outage (mo)	11.7	6.0	4.6	3.5
Probability of early termination (%)	9.5	4.0	1.2	.7
Excess program life (mo)	-10.0	-2.0	5.0	14.0

[a]Four satellite system for a five-year program.

work-arounds. Air Force requirements based on GAP analyses that fail to include the effect of work-arounds may seriously understate expected system performance.

The method of derivation of the reliability function with work-arounds is demonstrated sufficiently for the case of two work-arounds. First, choose a random number u_1 uniformly distributed on the range (0, 1). The probability density of u_1 is just du_1.

Second, choose a second random number u_2 uniformly distributed on the range (0, u_1). The probability density of u_2 is du_2/u_1, because it must be normalized to unity over the range (0, u_1).

Then choose a random number u_3 uniformly distributed over the range (0, u_2), whose probability density will be du_3/u_2. The simulated lifetime of the system will be $t(u_3)$, where $t(R)$ is the inverse function of $R(t)$. The expected value of the lifetime, T_2 denoting two work-arounds, is found by averaging over the permissible values of the three random numbers:

$$T_2 = \int_0^1 du_1 \int_0^{u_1} \frac{du_2}{u_1} \int_0^{u_2} \frac{du_3}{u_2}\, t(u_3) \ .$$

Integrate by parts on u_1:

$$T_2 = (\ell n\ u_1) \int_0^{u_1} \frac{du_2}{u_2} \int_0^{u_2} du_3\ t(u_3) \Big|_{u_1 = 0}^{u_1 = 1} - \int_0^1 du_1 \frac{\ell n\ u_1}{u_1} \int_0^{u_1} du_3\ t(u_3) .$$

The integrated term vanishes at $u_1 = 1$ because $\ell n\ 1 = 0$, and at $u_1 = 0$ because the integral vanishes faster than $\ell n\ u_1$ increases. Again integrate by parts:

$$T_2 = -\frac{1}{2} (\ell n\ u_1)^2 \int_0^{u_1} du_3\ t(u_3) \Big|_{u_1 = 0}^{u_1 = 1} + \frac{1}{2} \int_0^1 du_1\ (\ell n\ u_1)^2\ t(u_1) .$$

As before, the integrated term vanishes. The same process may be applied if there are k work-arounds:

$$T_k = \frac{(-1)^k}{k!} \int_0^1 du_1\ (\ell n\ u_1)^k\ t(u_1)$$

Because $t(u_1)$ is the inverse function to $R(t)$, the time may be introduced as the independent variable in the integral. The limits (0, 1) for u_1 become (∞, 0) for t:

$$T_k = -\frac{1}{k!} \int_0^\infty dt\ t(-\ell n\ R(t))^k\ dR/dt .$$

We also have, from the definition of the reliability function $R_k(t)$:

$$T_k = -\int_0^\infty dt\ t\ dR_k/dt ,$$

because the probability the system with k work-arounds survives to t and then fails is $-dR_k/dt$. Equating the two expressions yields:

$$\frac{dR_k}{dt} = \frac{(-\ln R(t))^k}{k!}\frac{dR}{dt}$$

$$R_k(t) = 1 + \int_0^t dt' \frac{(-\ln R(t'))^k}{k!}\frac{dR(t')}{dt'} .$$

Still another integration by parts yields:

$$R_k(t) = 1 + \frac{(-1)^k}{k!}\left[R(t')(\ln R(t'))^k \Bigg|_{t'=0}^{t'=t} = \int_0^t dt' \, R(t') \cdot k \cdot \frac{(\ln R(t'))^{k-1}}{R(t')}\frac{d\,R(t')}{dt} \right]$$

$$= 1 + \frac{R(t)\;(-\ln R(t))^k}{k!} + \int_0^t dt' \frac{(-\ln R(t'))^{k-1}}{(k-1)!}\frac{d\,R(t')}{dt'}$$

$$= R_{k-1}(t) + R(t)\;(-\ln R(t))^k/k! .$$

This recursion relation may be summed, starting with $R_0(t) = R(t)$, to yield the result:

$$R_k(t) = R(t)\sum_0^k \frac{[-\ln R(t)]^n}{n!} .$$